2014-06

COLREGS-Compliant Autonomous Collision Avoidance Using Multi-Objective Optimization with Interval Programming

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in partial fulfillment of the requirements for the degrees of
Naval Engineer
and
Master of Science in Mechanical Engineering
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2014

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From - To)* 15 May 2011-15 Jun 2014

4. TITLE AND SUBTITLE COLREGS-Compliant Autonomous Collision Avoidance Using Multi-Objective Optimization with Interval Programming	**5a. CONTRACT NUMBER** N00244-09-G0014
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Kyle Woerner	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943	**10. SPONSOR/MONITOR'S ACRONYM(S)** NPS
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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A testing metric was proposed for declaring AMVs as "COLREGS-compliant" for at-sea operations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Carol Stoker
			UU	111	**19b. TELEPHONE NUMBER** *(Include area code)* (831) 656-3025

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Submitted to the Department of Mechanical Engineeringon May 09, 2014, in partial fulfillment of the requirements for the degrees of Naval Engineer
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Abstract

High contact density environments are becoming ubiquitous in autonomous marine vehicle (AMV) operations. Safely managing these environments and their mission greatly taxes platforms. AMV collisions will likely increase as contact density increases. In situations where AMVs are not performing a collaborative mission but are using shared physical space such as multiple vehicles in the same harbor, a high demand exists for safe and efficient operation to minimize mission track deviations while preserving the safety and integrity of mission platforms. With no existing protocol for collision avoidance of AMVs, much effort to date has focused on individual ad hoc collision avoidance approaches that are self-serving, lack the uniformity of fleet-distributed protocols, and disregard the overall fleet efficiency when scaled to being in a contact-dense environment. This research shows that by applying interval programming and a collision avoidance protocol such as the International Regulations for Prevention of Collisions at Sea (COLREGS) to a fleet of AMVs operating in the same geographic area, the fleet achieves nearly identical efficiency concurrent with significant reductions in the collisions observed. A basic collision avoidance protocol was analyzed against a COLREGS-based algorithm while parameters key to collision avoidance were studied using Monte Carlo methods and regression analysis of both real-world and simulated statistical data. A testing metric was proposed for declaring AMVs as "COLREGS-compliant" for at-sea operations. This work tested five AMVs simultaneously with COLREGS collision avoidance–the largest test known to date.

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Acknowledgments

The work contained in this thesis would not have been possible without my colleagues, friends, and family who surrounded me each day.

To my colleagues in the Marine Robotics Group and the Laboratory for Autonomous Marine Sensing Systems, you proved invaluable at every turn in the work. Your continued support both professionally and personally has been unforgettable. The conversations we had greatly influenced my approach and thinking in the world of autonomy.

A very special thank you to Mike Benjamin for his guidance, continuous enthusiasm, and close friendship throughout this work. Without you, this work would not have been possible.

To my advisor, Professor John Leonard, I thank you for the many times that you cleared your schedule as I sought your advice and expertise. You have gone out of your way for me many times throughout this work, and for that I am incredibly grateful. I look forward to our continued work together in my doctoral studies these next couple of years.

To Alon Yaari, your technical expertise was invaluable. I cannot count the hours that you spent teaching me the ins and outs of marine autonomy both inside robots as well as in their ones and zeros. You might be the only person that I've met that could bring a fully submerged autonomy computer with a hull penetration back to life with just patience, compressed air, and a few spare parts. Your smile and eagerness when you teach will bring much value to the next generation of autonomy experts.

To Misha Novitzky, thank you for the countless hours of support in the very small hours of the summer months as we tried to beat the crew shells and sail boats to the Charles River. I never expected working in a lab so early in the morning could be so much fun. There are many great memories chasing our robots on the River as well as hiking out trying desperately not to capsize our super fast sailboat...again.

To my unofficial advisors, Professor Henrik Schmidt, Captain Mark Thomas, and Commander Jerod Ketcham, I thank you for the many conversations that have guided me to success. To the my colleagues whose help at the sailing pavilion and in CSAIL will never be forgotten, thank you for everything. A special thanks to Arthur Anderson, Mario Bollini, Tan Yew (William) Teck, the Dan Codiga and the University of Rhode Island team, the MIT 2.680 course staff, and certainly the many staff of the MIT sailing pavilion.

To Battelle, thank you for a fantastic laboratory and your support of the MIT autonomy community.

I am of course in debt to the United States Navy for their support and investment to allow me such an opportunity in the middle of my career.

A final thank you for the undying support of my fiancée, Daniela, and her never ending patience with my long hours of work, mistakenly missed meals, and seemingly never ending stories about those listed above.

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Chapter 1

Introduction

Currently fielded autonomous marine vehicles (AMVs) using collision avoidance behaviors operate with non-protocol based, often unpredictable, and sometimes grossly inefficient algorithms. Years of manned operations of seagoing vessels have shown that the use of an established protocol for collision avoidance (i.e., COLREGS[1]) results in predictable, safe, and efficient operation of vessels. Direct radio communication with another vessel is often unnecessary when visual or instrument-provided knowledge of location, heading, and speed are available and reliable during normal execution of a collision avoidance maneuver

1.1 The Necessity for Collision Avoidance

Rules for collision avoidance have been used as far back as 2200 years ago, though they have been constantly evolving and subject to the influence of rising and falling empires [33]. International conferences, rulings by Courts of Admiralty, and international treaties have all led to further clarification throughout the centuries on interactions of vessels. These rules have continued to adapt to an ever-expanding definition of sea-going vessel as technology progresses.

[1] COLREGS refers to international rules as formalized at the Convention on the International Rules for Preventing Collisions at Sea, developed by the International Maritime Organization, and ratified as an international treaty by Congress. These rules were further formalized by the U.S. International Navigational Rules Act of 1977 [1], and are sometimes referred to as the Collision Regulations outside the United States.

One thing that has remained consistent throughout the years, however, is the need for a clear protocol to guide captains and helmsmen in safe navigation when in proximity of other seagoing vessels. This is especially true when direct communication is not possible between vessels. By establishing a clear and consistent protocol for how to conduct one's vessel when in the proximity of other vessels, a captain can both predict the other vessel's movements as well as prevent concurrent, symmetric maneuvers that place the vessels at risk of collision[2].

1.2 The Advantage of COLREGS for AMVs

Since 1972, COLREGS have been the predominant set of rules for prevention of collisions at sea. Amendments to COLREGS became effective internationally in 1995 after the International Maritime Organization adopted the amended rules in 1993 [1]. While COLREGS do not prevent collision without both knowledgeable and correct application of the rules, they do establish a framework of consistency between mariners that allows for anticipation of vessel maneuvers based on its protocols. While these rules are delineated in a hierarchical fashion for types of craft (e.g., sailing vessels, powered vessels, fishing vessels, etc.), the rules further delineate protocol based on how vehicles of an equivalent class[3] encounter each other. For example, Rule 13 of COLREGS specifically addresses a power-driven vessel who is overtaking another power-driven vessel. The rules and their context are further discussed in Section 3.3.

These rules were intentionally written as to not be an exact if-then type algorithm but rather composed to be open for human judgment and interpretation. In an environment where autonomous marine vehicles interact solely with other autonomous marine vehicles, a different protocol could be adapted so long as it is consistent and efficient for interactions. With the rising presence of autonomous marine vehicles in the vicinity of manned vehicles, having a separate protocol for manned and unmanned

[2]A symmetric maneuver refers to an encounter which results in both vessels turning toward the same cardinal direction often resulting in an impending collision scenario. Symmetric maneuvers are further discussed in Section 2.4.1

[3]The term "class" here refers to two vessels in the same section of the Rules such as two sailing vessels or two power driven vessels.

vehicles would result in both confusion and inefficiency, especially in the case where a vessel's operator (either captain or computer) is unable to tell if the other is manned or unmanned. For consistency across the maritime spectrum and ease of application of the rules to all situations where a vessel (manned or unmanned) is encountered, the only logical conclusion is to fit autonomous marine vehicles with a COLREGS-based protocol.

1.3 Potential Applications of COLREGS-Compliant AMVs

For autonomous marine vehicles, managing a contact-rich environment to prevent collisions while still accomplishing their mission greatly taxes platforms, and a legitimate concern exists that AMV collisions could become more frequent. In situations where AMVs are not necessarily performing a collaborative mission but are using shared physical space such as multiple vehicles running on the same river or open ocean area, a high demand exists for safe and efficient operation to minimize mission track deviations while preserving the safety and integrity of marine platforms. The ability for several autonomous marine vehicles to collaborate with each other absent direct communication (other than knowing the other vessels position over time) is of high desire to industry, academia, and military applications [19, 34].

A tradeoff must often be made by the mission planner between safely operating an autonomous craft and compromising significantly on mission efficiency usually due to poorly executed, symmetric maneuvers. These symmetric maneuvers[4] often result in one or both vessels requiring a complete circle pattern in order to avoid collision and return to the intended track or even worse an actual retreat toward the heading opposite of that desired in order to avoid a collision.

By having a predictable protocol, actual track deviation for collision avoidance maneuvers should be equivalent or reduced on average compared to a non-protocol based algorithm allowing for fewer distractions from the vehicle's intended mission.

[4] Symmetric maneuvers are discussed in detail in Section 2.4.1.

By focusing on efficient mission execution, autonomous marine vehicles would realize a significant gain in safety without cost to overall efficiency. Further, knowing expected maneuvers will allow for safer navigation by all vessels.

Once proven with many interactions between several COLREGS-compliant autonomous marine vehicles, this solution can eventually be scaled to allow interaction with manned surface vessels. Ideally, the adaptation of COLREGS into the normal operating behaviors of autonomous marine vehicles would allow for proper collision avoidance maneuvers regardless of the other vessel being manned or unmanned. With the proper input of the other vessel's data by means such as shared GPS, AIS, visual detection algorithms, RADAR, and other means, the AMV can correctly determine the appropriate maneuver and take action as if it were itself a manned vessel.

The impact of autonomous marine vehicles correctly interacting with manned vessels will be realized immediately throughout the world. Some autonomous tankers making transoceanic voyages currently would use a vehicle following approach where they mimic a manned vessel in their convoy. To allow the autonomous tanker to transit unaccompanied would prove financially attractive to the operator [34]. Current research vessels collecting marine data must broadcast a notice to mariners in coordination with the Coast Guard, though the incorporation of compliance with COLREGS should alleviate this requirement and allow for scaling of autonomous research craft to much more powerful numbers. The data collection impact could be quickly seen in areas where gliders cannot currently reach but marine traffic is too high for an effectively blind AMV such as the littorals.

1.4 Literature Review and Recent Research

Various approaches have been investigated over the past decade to solve the collision avoidance problem for autonomous marine vehicles. The evolution of the role of autonomous vehicles within the framework of interacting with manned vessels still requires resolution [14] and will likely be seen in the years to come as an ongoing debate. While current desires are to integrate COLREGS into AMV behaviors, several rudimentary solutions have been used to date that seek a greedy solution with disregard to global efficiency of all vehicles in the mission environment. Other solutions are less greedy though are limited to canonical geometries, fail to address more than one COLREGS rule, study only single pair vehicle interactions, use non-dynamic target vessels, or are implemented in simulation environments not readily scalable to field testing on autonomous marine vehicles.

Testing within COLREGS for autonomous marine vehicles (especially with studies that used in-water validation of their simulations) was initially based on limited scenarios consisting of canonical geometry. Benjamin et al [7, 8] evaluated single vehicle pairs while testing several COLREGS rules with a solution based on multi-objective optimization with interval programming. In-water validation was conducted, though the scope was limited to "canonical collision risk situations." This is believed to be the first in-field demonstration of collision avoidance using COLREGS on autonomous marine vehicles. The Benjamin study used MOOS-IvP [5] which provides a set of open source C++ modules for robotic autonomy with focus on autonomous marine vehicles. MOOS-IvP – built for problems requiring multi-objective optimization – proves to be a powerful platform for autonomous marine vehicles due to its ability to test in simulation and then immediately test on real vehicles operating on the water. The Benjamin research proved to be advantageous to other research in this field with respect to its ability to readily field test whereas many other researchers chose to simulate in an environment such as MATLAB without any real world data gathering capabilities. An example from Benjamin's published research is shown in Figure 1-1.

Other developers have chosen to use algorithms designed to achieve collision avoidance by implementing emergency reactive behaviors [11]. The work by Evans uses a singleton fuzzier and Mamdani reasoning to generate outputs from combinations of if-then rules. This approach seems to be effective in the limited testing conducted at the time with the testing-friendly scenarios. These behaviors however would not be appropriate for use in a COLREGS-based scenario with surface craft unless used as

[5]MOOS-IvP is short for Mission Oriented Operating Suite with Interval Programming, available at http://moos-ivp.org.

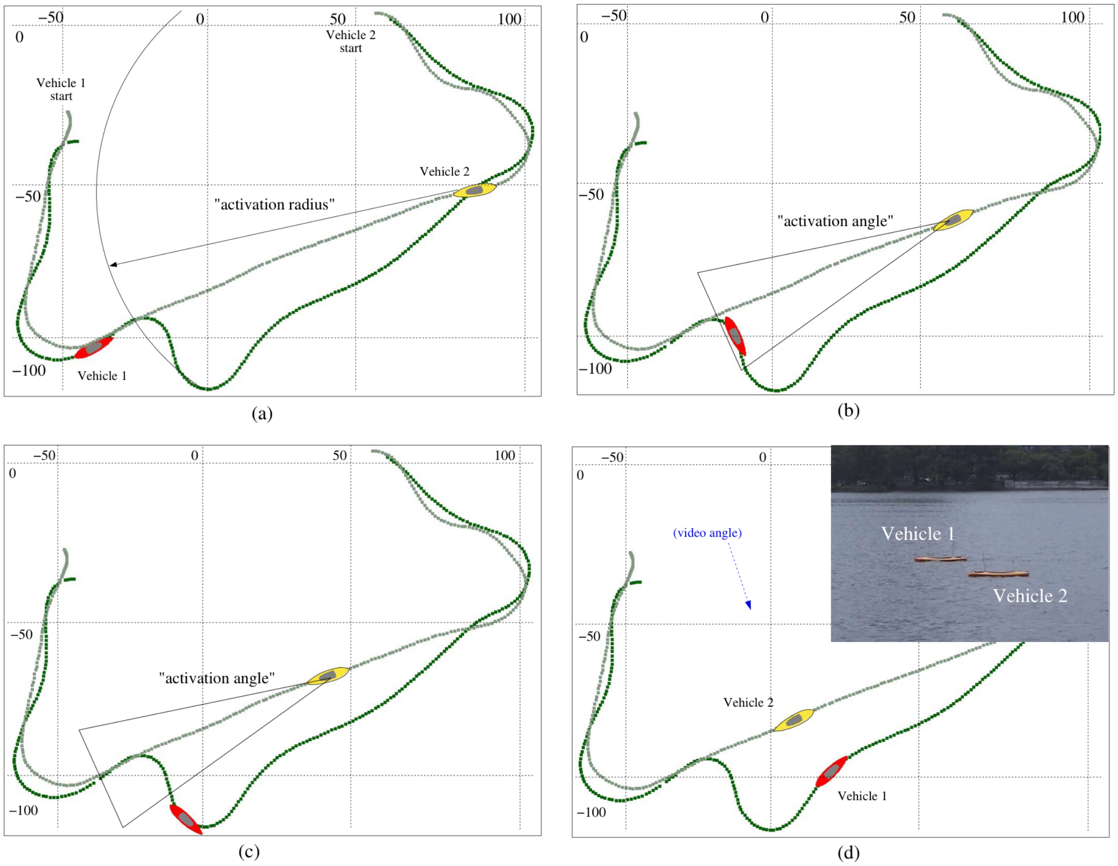

Figure 1-1: Benjamin et al demonstrated on water successful testing of COLREGS using single vehicle pairs in limited single vehicle pair scenarios. Several COLREGS rules were tested though only one at a time. Image from [7, 8].

a last effort to avoid collision in parallel with a protocol-compliant rule set.

A solution focusing on insertion of a heading bias to starboard was conducted by Teo et al [31]. The solution "handle[d] static and moving obstacles in head-on situations in accordance to the COLREG Rule." Teo demonstrated that a turn to starboard was possible for single contact encounters with head-on geometry. The approach suppressed both obstacle avoidance and goal seeking behaviors when a risk of collision was detected. An example of Teo's work is shown in Figure 1-2.

Another simple manual biasing scheme (again, a turn to starboard) was later performed by Naeem et al [24] when an obstacle's range fell within a pre-defined circle of rejection. The goal of the study was to integrate COLREGS into a path planning algorithm. The study focused on showing success for scenarios with multiple

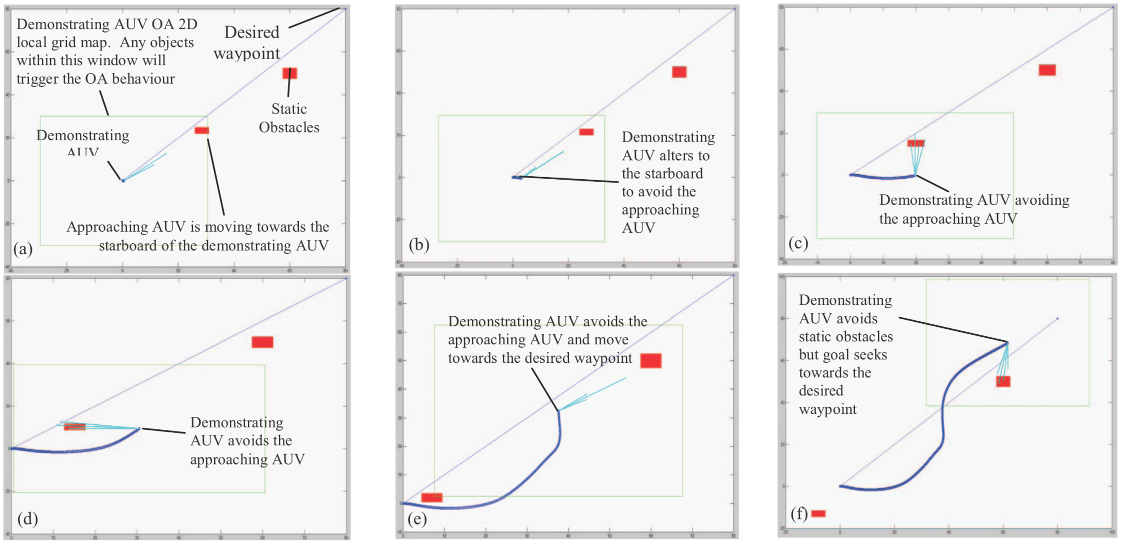

Figure 1-2: Teo et al demonstrated turns to starboard using single contact pairs in head-on scenarios. Image from [31].

stationary hazards and a single dynamic hazard (vessel). Heading bias solutions were a great stepping stone for the field to see that actions could indeed be taken, though refinement was necessary to prevent excessive maneuvers resulting in unnecessary and inefficient deviations from intended track. The Naeem research was a powerful step in that it introduced both static and dynamic targets. The single dynamic target resulted in crossing the ship's path twice due to its reciprocal maneuver after the first interaction. An example from Naeem's work illustrating the approach is shown in Figure 1-3.

Fuzzy logic implementation was realized by Perera et al [27] using MATLAB-based if-then logic. A vessel deemed to be in a stand-on position relative to the other vessel was allowed under this solution to take emergency action if a determination was made that she was in extremis[6]. Perera used the fuzzy logic approach to overcome crash-stops that might otherwise occur if a collision were imminent. This study was limited to a single vehicle pair and an example image of Perera's work is shown in Figure 1-4.

A follow on study was conducted by Perera et al [28] to address sequential vehicle

[6]This action is in accordance with Rule 17(a)(ii) of COLREGS [1]

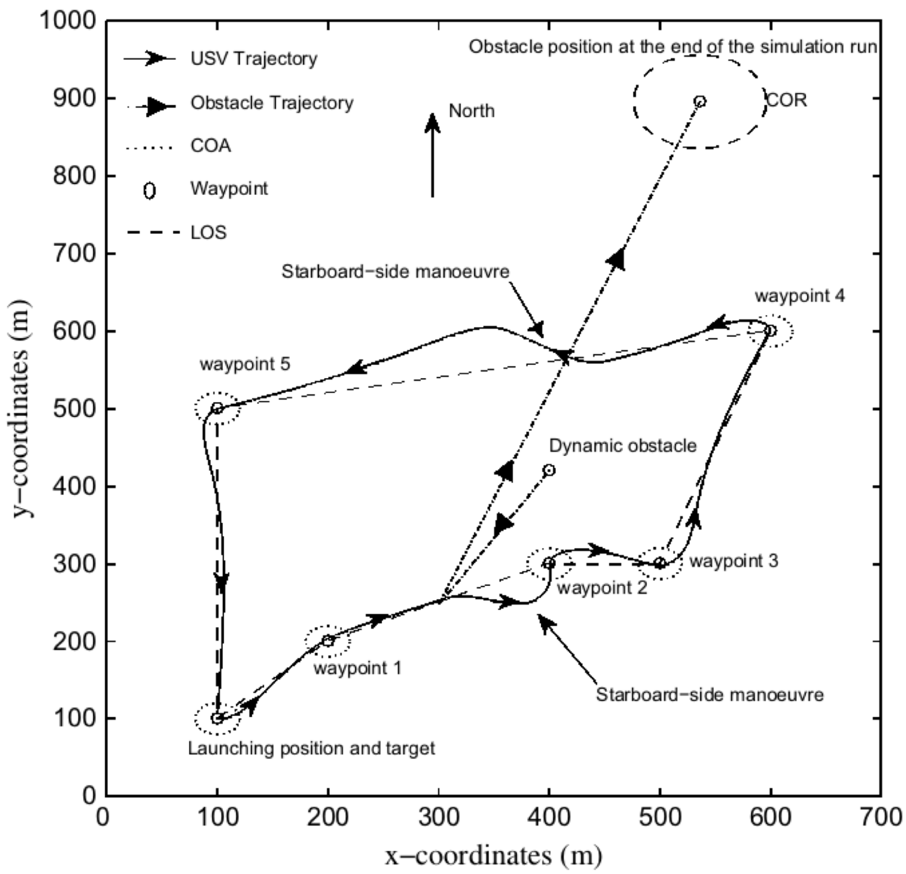

Figure 1-3: Naeem et al showed that multiple stationary hazards and a single dynamic hazard could be avoided using a simple manual biasing scheme with a turn to starboard. [31].

interactions by demonstrating evasive maneuvers as a vessel crossed a simulated navigation lane with three non-COLREGS-compliant vessels. Two pre-defined situations were used: one with canonical geometry in 90 degree crossing scenarios, and a second with a canonical crossing, a non-canonical crossing, and an overtaking encounter occurring sequentially. Throughout this study, the opposing vessels were pre-positioned in their pre-defined velocity and heading states. The target vessels maintained course and speed throughout their transit. Of note, a questionable approach is taken to have the "COLREGS-compliant" vessel turn to port as the stand on vessel when a non-compliant give way vessel continues on course and speed as this violates COLREGS. This study showed a vehicle maneuvering in extremis using a change of course to port during two subsequent maneuvers for a vehicle on her port side in direct violation of

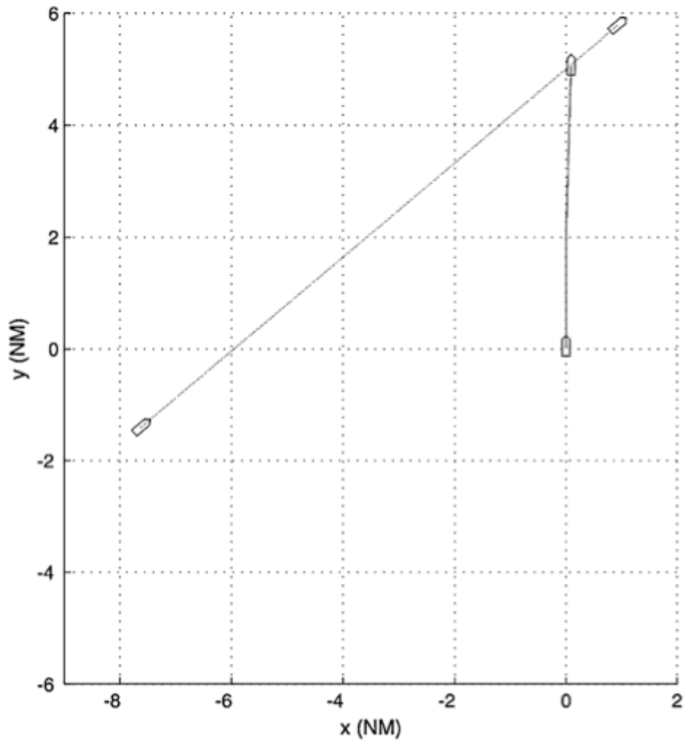

Fig. 24 Crossing situation

Figure 1-4: Perera et al showed that fuzzy logic based decision making could be used for collision avoidance in ocean navigation under critical collision conditions. This research was based on a single vehicle pair interaction. Image from [27].

Rule 17 (c) of COLREGS.

While the basic validation of COLREGS compliance for autonomous marine vehicles has yet to be achieved, other studies have worked to refine sensing capabilities to integrate into their collision avoidance solutions. Naeem et al [25] used a high-definition camera with a laser range finder to further add to their contact picture. A Kalman filter estimation of position and track was realized. These solutions were then used to integrate vessel dynamics into their existing work with a goal of continuing COLREGS-capable path planning. Another approach by Bibuli [9] examined vehicle following of a manned vehicle which is passing its position, course, and speed to the autonomous vehicle. This work claimed that basic vehicle following concerns were solved and virtual target-based guidance was validated.

A final type of approach for AMV collision avoidance uses velocity obstacles such as the work by Kuwata et al [17,18] by inserting additional constraints on the velocity

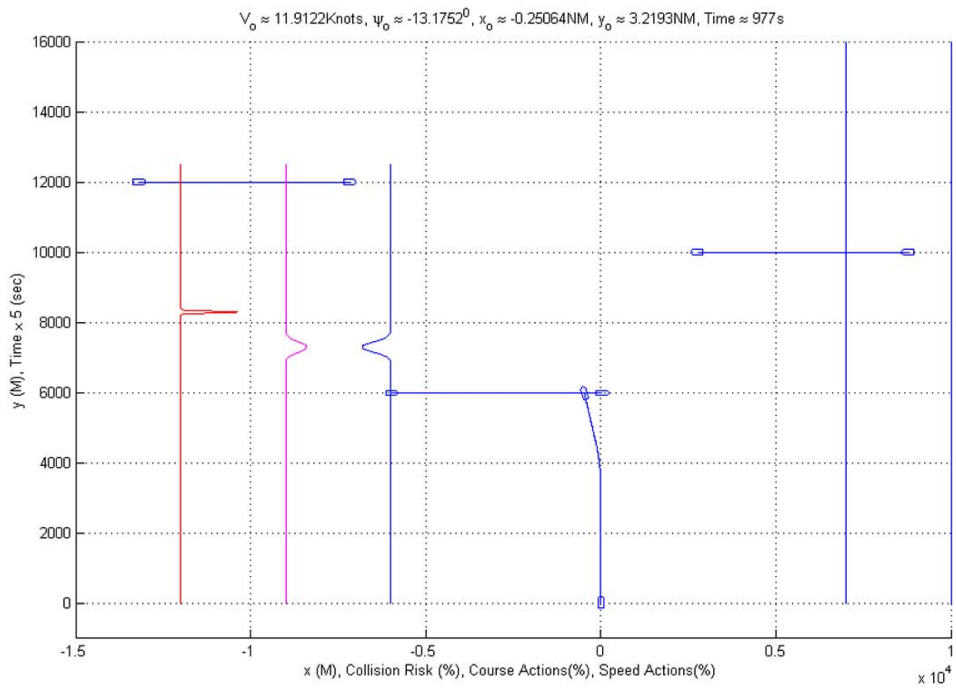

Figure 1-5: Perera et al showed in their 2012 research that multiple successive (not concurrent) vehicle interactions could be considered in their fuzzy logic MATLAB-based approach. Image from [28].

decision space by applying an appropriate collision avoidance algorithm to account for both static and dynamic hazards as shown in Figure 1-6. This work, however, inappropriately declares that when a vessel is "... crossing from the left, there is no COLREGS constraint..." though the Rule 17 (a)(i) of COLREGS clearly outlines that the stand on vessel is required to maintain her course and speed. This approach would prove to violate COLREGS in a case where the mission desired a significant course change but the rules dictated a constant course and speed. Kuwata's solution also claimed to "... execute the maneuver for a duration of time thereby making the USV's decision more obvious and predictable to human drivers on other vessels." This, however, should not be temporal, but rather geometry based. The Rules are written in a completely spatial context with no regard for time other than implicitly allowing the operator to determine when a "risk of collision exists." A velocity obstacle approach is further limiting by only precluding bad maneuvers without also encouraging maneuvers whose CPA range would be larger than the minimum acceptable CPA range.

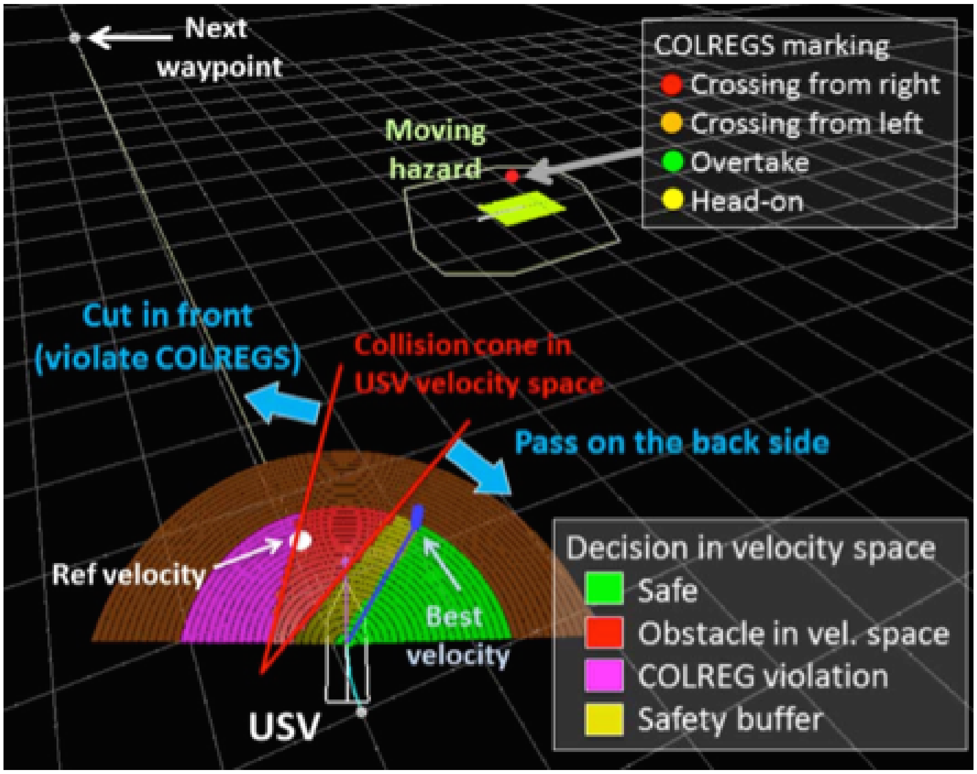

Figure 1-6: Kuwata et al showed in their 2014 research that velocity obstacles was an alternative approach to using a CPA-based collision avoidance algorithm. Image from [17, 18].

While research conducted in the area of COLREGS-compliant collision avoidance for autonomous marine vehicles has certainly progressed greatly in recent years, many areas require further advancement. Several of the limitations of current research which have been either understudied or unstudied are summarized in the following list.

1. Vehicles have been limited to interactions in single vehicle pairs. While multiple interactions may occur within one test, they have almost always been designed to occur sequentially as to not start a subsequent interaction until full resolution of the existing collision situation has been achieved.

2. Single rules have been evaluated at any one time. While some researchers studied more than one collision avoidance rule, the testing of these multiple rules occurred in a sequential rather than concurrent format resulting in a series of single tests. A true analysis of multiple concurrent rules similar to how real-world open-ocean decisions are made on the bridge of a ship is more relevant.

3. Target vessels have often had static characteristics in that they either maintained course and speed throughout the collision avoidance testing or were declared as a static object with no speed and thus a fixed position.

4. Most tests focused on canonical geometry. Many of the collision avoidance scenarios for crossing situations have had nearly orthogonal tracks for the target vessel and own-ship. For head-on and overtaking scenarios, most tests have occurred in similarly near-ideal geometries.

5. Many studies have produced simulations in programming environments that cannot be replicated on actual autonomous marine vehicles. Programming environments such as MATLAB are incredibly powerful but do not offer easy replication with in-field testing environments.

1.5 Contribution of this Research

This research focused at proving the hypothesis that a COLREGS-based collision avoidance protocol for autonomous marine vehicles could provide both high safety and efficiency. The work further investigated the direct effects on safety and efficiency through a design of experiments with a regression analysis that varied key collision avoidance parameters. The resulting collision avoidance algorithms now have the potential to be used worldwide on autonomous marine vehicles running the MOOS-IvP software architecture for use with other autonomous marine vehicles as well as integration into manned surface vessels interactions. Simulated results were validated with in-water testing on vehicles running the same missions. The number of vehicle encounters in simulation and in-water testing sufficiently validated the analysis. On-water testing involved scenarios including up to five autonomous marine vehicles concurrently avoiding each other using COLREGS.

To advance recent work in the area of collision avoidance for autonomous marine vehicles, achieving successful resolution or improvement in the areas identified in Section 1.4 was highly desired. Based on the aggregate of the studies previously mentioned, various areas were identified as significant value to the field if occurring simultaneously in a single study. The following list summarizes the characteristics accomplished in conjunction with fulfilling the larger goal of this work which is described in detail in Section 1.5.1. These characteristics were leading motivators for the way in which this work's research was conducted.

1. Robust COLREGS-compliant AMV algorithms were developed.

2. More than two vehicles interacted concurrently. Studies to date focused on single-pair vehicle interactions that occur in succession after a collision avoidance has fully (or nearly fully) resolved.

3. Multiple rule scenarios tested (head-on, overtaking, and crossing) concurrently. Testing of multiple scenarios occurred simultaneously (e.g., own-ship was head-on with target vehicle 1 while simultaneously concerned with crossing target vehicle 2's track).

4. Target vessels possessed dynamic characteristics (both with and without COLREGS-compliant behaviors). Target vessels maneuvered for their own mission purposes[7] and did not only maintain course and speed (unless assigned as the stand-on vessel in accordance with the Rules).

5. Tests occurred with non-canonical geometry. While a standard shape could be used for general tracks to be followed by vehicles, the vehicles maneuvered for collision avoidance and naturally found themselves off the prescribed track resulting in non-canonical geometries.

6. Use of the MOOS-IvP software environment allowed for simulations to be easily replicated on vehicles in the field.

7. A tradespace analysis examined the effects of key collision avoidance parameters on both safety and efficiency.

[7] Missions that require track deviation might include autonomous acoustic sensing, non-linear navigational tracks such as a predetermined turn for transiting, or underwater mapping.

8. Simulations consisted of extensive number of interactions to allow for long duration results as shown in Table 1.1. An estimated 29+ hours of COLREGS based on-water experimentation and 85+ hours of the non-protocol based on-water experimentation was used for improvement to the algorithms and verification of consistency with simulated data.

Total Interactions Simulated	
Non-Protocol Algorithm	329764
COLREGS Algorithm	419382

Table 1.1: Extensive simulations were analyzed for both the COLREGS-based and non-protocol based algorithms.

9. Significant robustness testing with up to seven vehicles in simulation in close proximity allowed for extensive edge case searches.

10. Testing and certification requirements for AMVs as well as modifications to COLREGS to incorporate autonomous marine vehicles were recommended.

11. A new collision avoidance behavior library was written and published for the MOOS-IvP autonomy software.

1.5.1 Problem Formulation and Approach

The goal of this research was to show that the addition of a COLREGS-compliant collision avoidance protocol into autonomous marine vehicle routines would establish high overall efficiencies and significantly improve safety compared to non-protocol based collision avoidance algorithms by reducing the number of collisions[8] that occur. To achieve the desired efficiency and safety combination, key collision avoidance parameters were identified and values that maximize both efficiency and safety were determined through regression testing and analysis in several collision avoidance scenarios. This analysis was conducted by comparing results to the baseline of having a basic, non-protocol based set of collision avoidance maneuvers available to the AMV

[8]The term "collision" refers to a violation of a safety range as discussed in Section 2.4.1 and does not necessarily indicate physical contact between two vehicles.

and similar to those used on many autonomous marine systems in use at the time of this writing. To adequately evaluate this efficiency-safety tradespace for autonomous marine vehicles, large numbers of Monte Carlo simulations were performed to analyze the impact of specific variables of interest. Both in-water and computer simulated trials were conducted with the former validating the latter.

This research analyzed performance between autonomous marine vehicles undergoing various missions while simultaneously avoiding collision with other vessels. A design of experiments with regression analysis was used to determine the most influential variables within a collision scenario to effectively drive efficiency to a maximum value while achieving maximum safety. Efficiency was measured with respect to additional distance traveled from a contact-free baseline track to complete the prescribed mission. Safety was measured by considering any actual range that was closer than a nominal threshold value to be a collision.

A further goal of this research was to establish criteria for acceptance of an unmanned surface vehicle as being "COLREGS compliant." This portion of the research focused on a more qualitative exploration of how COLREGS (written with manned vessels in mind) could be extrapolated to include unmanned vehicles while still honoring the spirit of the original instruction. This lead to incorporation of these results into a recommended mandated series of tests for autonomous vehicles to show compliance with various rules in a series of canonical and non-canonical scenarios exemplifying various COLREGS rules of interest.

1.5.2 Assumptions and Scope

Assumptions used throughout this research include the following:

1. This work was limited to determining a solution to collision avoidance of autonomous marine vehicles assuming that reliable and accurate contact detection, classification, and tracking were already available. While other studies have focused on achieving more accurate and robust detection and tracking mechanisms, the ideal contact detection case was considered for the purpose of this

work in order to pursue refinement of actual collision avoidance performance rather than position sensing.

2. GPS was assumed to provide sufficiently accurate and precise location data for in-water testing.

3. A worst-case two-vehicle collision geometry with GPS receiver to maximized GPS receiver distance was assumed based on non-body centered GPS antenna placement. An additional safety margin was added to this distance to provide further margin for safe in-water testing (see Section 2.4.1).

4. All vehicles within the testing space were autonomous and running the MOOS-IvP system architecture.

5. All vehicles within the testing space were further restricted to being in the same shoreside environment allowing for a single shoreside display of all vehicles on one screen (described in Section 2.2).

6. A collision existed if a nominal threshold value of range to a contact was violated[9].

7. All hazards to navigation such as buoys, day markers, and anchored vessels were excluded from the testing space.

This project was limited to autonomous marine vehicles and encourages future research to integrate AMV collision avoidance with manned contacts. The application of external contact sensors such as RADAR was outside the scope of this research and would be necessary for integration into a contact environment involving manned vessels where automated systems such as AIS cannot be guaranteed.

1.5.3 Criteria for Success

Several criteria for success were considered and include the following.

[9]The assumed nominal range of a collision throughout this work was three meters. This was based on a GPS-to-GPS distance of approximately two meters for the worst case geometry of the vehicles studied in addition to a one meter safety stand-off range.

1. Multiple COLREGS rules tested successfully.

2. Multiple COLREGS rules tested simultaneously.

3. COLREGS rules tested in conjunction with mission objectives.

4. More than two vehicles interacted concurrently.

5. Target vehicles were dynamic with respect to course and speed.

6. Performance evaluations used non-canonical encounter geometries.

7. Evaluation used a vehicle-friendly software environment for validation with in-water testing.

8. Number of encounters in collision scenarios was sufficiently large to validate results.

9. In-water testing validated simulation data.

10. Identification and analysis of significant collision avoidance parameters achieved.

11. A collision-avoidance "road test" for autonomous marine vehicles recommended for use in real-world applications.

1.5.4 COLREGS Behavior for MOOS-IvP

The COLREGS-based collision avoidance behaviors for this work were developed in an open source architecture called MOOS-IvP which is an extension to the more general MOOS environment. The Mission Oriented Operating Suite (MOOS) was written by Paul Newman in 2001 with the intention to "support operations with autonomous marine vehicles in the MIT Ocean Engineering and the MIT Sea Grant programs [5]." At the time of this work, MOOS was being used to drive the University of Oxford's RobotCar UK[10] – a fully autonomous vehicle under design and testing by the Oxford

[10]University of Oxford's RobotCar UK website: http://mrg.robots.ox.ac.uk/robotcar

Mobile Robotics Group – in addition to use on autonomous marine vehicles around the world.

Interval programming (IvP) uses piecewise linearly defined objective functions to approximate underlying and often more complicated functions. Interval programming functions are a collection of IvP functions that each have an associated priority weight [3, 6]. IvP functions are defined in [6] as follows: "An IvP function is piecewise defined such that each point in the decision space is covered by one and only one piece, and each piece is an IvP piece... An IvP piece is given by a set of intervals, one for each decision variable, and an interior function evaluating each point in the piece." The priority weightings represent the importance of the associated objective function to the problem as a whole; these priority weightings are often dynamic and an important aspect to the designer's consideration. Using interval programming (IvP), the MOOS-IvP software extension was created by Dr. Michael Benjamin in 2004 to implement behavior coordination using multi-objective optimization [4]. The IvP Helm[11] application is used primarily to allow autonomous marine vehicles to perform missions within a prescribed operating area. Both surface and underwater autonomous vehicles are supported within this architecture. MOOS-IvP is a platform-independent software suite which can run on various classes of autonomous marine vehicles. This proved advantageous not only for testing, but further expanded the ability of the results of this work to be used on various AMV platforms around the world. Further discussion of MOOS-IvP and its use in COLREGS research is in Section 2.1.

A major part of this research included developing algorithms for incorporating the manned vessel collision regulations of COLREGS into the decision space of MOOS-IvP. A library of behaviors that incorporated the COLREGS power driven vessel rules were developed under the name BHV_AvdColregs. Collision avoidance between vehicles operating MOOS IvP have traditionally used the generic non-protocol based collision avoidance behavior BHV_AvoidCollision, though now they will be

[11]The proper name of IvP Helm application within MOOS-IvP documentation is pHelmIvP. More information can be found in [5].

able to have COLREGS compliance of power driven vessel rules by switching to BHV_AvoidColregs. The algorithms are discussed in more detail in Chapter 3 including a discussion of the difference between a protocol and non-protocol based approach in Section 3.2.

1.6 Thesis Overview

Chapter 2 describes the methods used to test COLREGS on autonomous marine vehicles to include the software, AMV platforms, geometries, metrics, and tools. Chapter 3 describes the standard closest point of approach algorithm and the newly developed COLREGS based algorithms for MOOS-IvP as well the development and testing of COLREGS-based algorithms in this work. Chapter 4 describes the regression testing and analysis performed in simulation using a design of experiments which determined the collision avoidance parameters that were most influential in finding the balance of safety and efficiency. Chapter 4 further describes the results of both in-water and simulated testing including a discussion of in-water testing performed with five autonomous marine vehicles concurrently. Chapter 5 describes a proposed standard for autonomous marine vehicles to be certified as COLREGS-compliant including recommended changes to COLREGS, metrics for certification, required technological advancements, and identification standards. Chapter 6 discusses conclusions of this work as well as recommendations for future studies. Regression testing data, framework, and detailed results can be found in the appropriate appendices.

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Chapter 2

Method of Analysis

2.1 MOOS-IvP Software Architecture

MOOS-IvP was used for the development of COLREGS at MIT as introduced in Section 1.5.4. MOOS-IvP operates using a publish-subscribe architecture allowing a shoreside station and autonomous marine vehicles to communicate and share information as required. Each vehicle in this work had its own MOOS community running onboard to perform its required operations including autonomous decision making and interaction with its own vehicle such as sending command signals to motor controllers. Each vehicle also communicated with the shoreside MOOS community to publish information as requested by shoreside (including information deemed necessary for safe operations of the fleet) as well as receive information that the shoreside or the vehicle had deemed important to its operations.

IvP Helm allows each active behavior to produce a piecewise linearly-defined objective function for evaluation in conjunction with all other active objective functions. During each iteration of the IvP Helm, a solver will achieve a single output heading and speed based on the weights and composition of the various objective functions produced by each active behavior of the current mission.

The solver onboard each AMV considers and solves for the resultant maneuver (ordered course, speed, and depth) using

$$\overrightarrow{x^*} = argmax_{\overrightarrow{x}} \sum_{i=1}^{k} (w_i \cdot f_i(\overrightarrow{x}))$$

where each $f_i(x_1, ..., x_n)$ is an objective function for the i^{th} of k active behaviors within MOOS-IvP. For the purpose of this work, only surface vehicles were used so depth was never considered. The specific objective functions and their associated weighting schemes are further discussed in Chapter 3 and Section 2.5, respectively.

2.2 Testing Environment and Hardware Used

The in-water portion of this research was conducted on the Charles River on the shores of the MIT campus between the cities of Boston and Cambridge, Massachusetts. The primary facility for launching and recovering autonomous marine vehicles as well as safety supervision of the testing area was the MIT sailing pavilion shown in Figure 2-1.

Figure 2-1: The primary facility for launching and recovering autonomous marine vehicles as well as safety supervision of the testing area was the MIT sailing pavilion on the Charles River in Cambridge, MA.

2.2.1 Shoreside Station

A wireless network was established spanning the entire testing area. The network was limited to use by only autonomous marine vehicles operating under supervision of the research laboratory at the MIT sailing pavilion. A combination of dockside observation, in-water patrol with motor boats, and frequent observation by the shoreside operator using dock-mounted webcams was essential to maintain a safe testing area. This was especially important as non-autonomous hazards such as crew shells, sail boats, and other recreational users of the Charles River were not uncommon.

pMarineViewer

An application within the MOOS-IvP suite that proved invaluable to both simulated and in-water mission testing was pMarineViewer. This tool allowed the user on the mission's shoreside server to have real-time observation of vehicle positions, tracks, active behaviors (including collision avoidance being undertaken), and vehicle status. The pMarineViewer was the overall controller for each mission and served as the first line of safety for mission execution. All vehicles received orders to deploy, return, station keep, and come to all-stop through operator action in pMarineViewer. Any safety observer was capable of requesting a stop in any mission which was then achievable within pMarineViewer. This safety measure proved highly useful in the testing environment on the Charles River where numerous small craft shared the water space. An example view of the pMarineViewer application with aerial superposition of the testing environment is shown in Figure 2-2. Any application using "AppCasting" would have its pertinent information displayed along the left side of pMarineViewer as shown in Figure 2-2.

iHealth

The iHealth tool was created during testing for collision avoidance to analyze and broadcast important information about vehicle health of in-water test vehicles. Important information such as average drawn current, battery voltage, and over-current

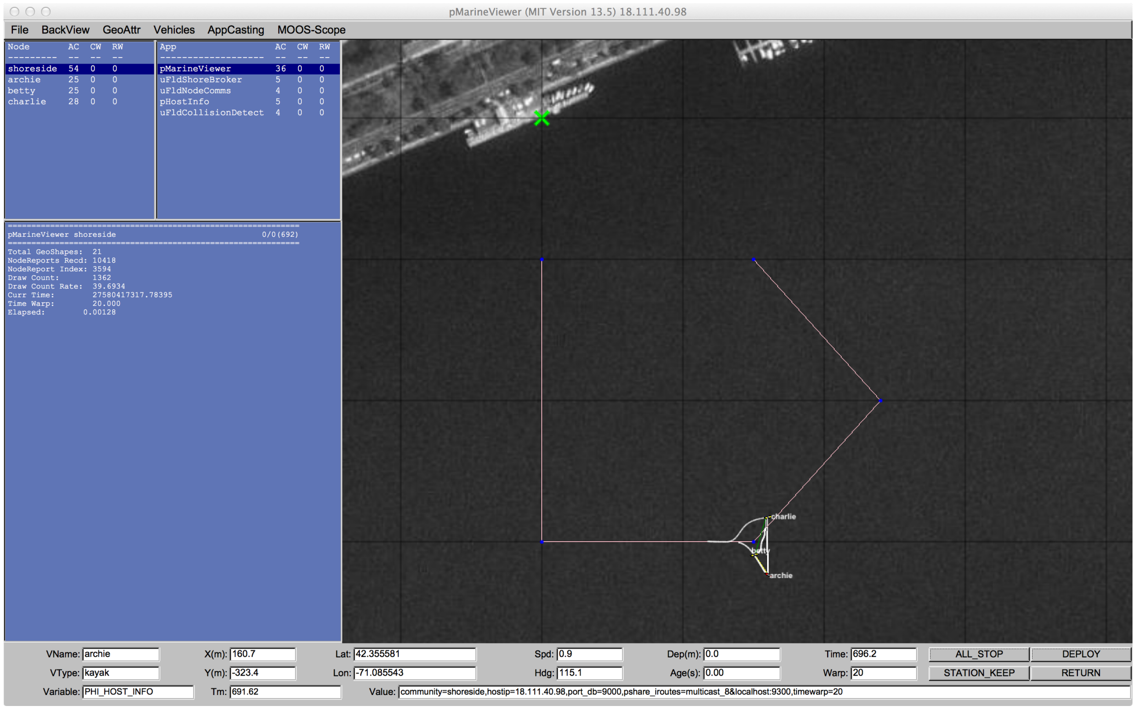

Figure 2-2: The pMarineViewer MOOS app is the primary graphical display used for marine autonomy experiments. The important information of each MOOS app was available along the left side using AppCasting. The vehicle data was overlaid on the appropriate image on the main part of the display. In this image, the MIT sailing pavilion laboratory can be see in along the upper left corner of the aerial view.

warnings were broadcast back to the shoreside server for each vehicle in real-time. The shoreside server operator was then able to quickly see if a vehicle had a condition such as a low battery voltage that would require operator action. This proved especially important because in-water testing with a vehicle whose battery voltage dropped below a critical value often resulted in insufficient power to safely maneuver as required to prevent a collision. The iHealth tool broadcast its information in AppCasting format to pMarineViewer for ease of operator use.

2.2.2 Autonomous Marine Vehicles

Two classes of autonomous marine vehicles were used for the work of collision avoidance: the Clearpath Kingfisher M100 and the Clearpath Kingfisher M200. Both the M100 and M200 models were fully autonomous with an override capability to drive using a radio frequency controller for emergency situations (such as unexpected crew shells rowing through the operating area). The operating systems on each model of vehicle were quite similar though several upgrades were achieved between the two models. With the use of a common language to interface with each vehicle's front seat, the actual model of vehicle became moot to the collision avoidance software given similar geometric dimensions of the vessels. Once each class of AMV was able to communicate on a lab-established wireless network, installation and configuration of MOOS was all that was required to integrate the vehicle into the testing environment. The MOOS environment allows for any type of vehicle running its software to interact with all other vehicles running MOOS that are in the same subnet[1]. By design, all vehicles within our testing space were restricted to being in the same subnet for safety reasons (see Section 1.5.2).

The M100 variant is a trimaran with propeller-driven propulsion on both port and starboard sides as shown in Figure 2-3. The M200 variant is a catamaran with water jet propulsion used as a second hull type for in-water testing as shown in Figure 2-4.

Figure 2-3: The Clearpath M100 autonomous marine vehicle is a trimaran with port and starboard fixed pitch propeller drive used for testing on the Charles River.

2.2.3 Simulation Environment

All real world vehicles and the environment were simulated in MOOS-IvP for more long duration simulations especially for use in the design of experiments. The only

[1]Inter-vehicle communication in simulation and on-water testing was conducted using wifi. Inter-vehicle communication in real-world applications where subnet sharing is unavailable would be realized through means such as AIS.

Figure 2-4: The Clearpath M200 autonomous marine vehicle is a catamaran, water jet driven design used for testing on the Charles River.

changes required to shift between real world and simulation could be achieved in seconds with a few lines of code to engage or disengage the simulator and switch the vehicle communications to the front seat off. This also allowed switching types of vehicles (for example, from M100 to M200 platforms) by simply changing which front seat was being used. By simulating in an environment where all else was held equal, more realistic simulation results were achievable.

2.3 Closest Point of Approach

Collision avoidance of marine vehicles is often performed while considering the closest point of approach (CPA). CPA is the global minimum value of range from ownship to a contact when evaluated over all future time while assuming both vessels maintain their current course and speed[2]. For the experienced seaman, any target vessel with a constant bearing and decreasing range is known to have a CPA range equal to zero, or in other words, a guaranteed collision. Simply avoiding an actual collision is often insufficient. Vessels are often interested in maintaining all other vessels outside of a particular CPA range based on the current contact picture and environmental conditions.

To find CPA range, the two vessels positions ($\xi \equiv (x, y)$), headings[3] ($h \equiv \phi$),

[2]CPA range is the global minimum range for a given vehicle pair. For brevity, CPA and CPA range are interchangeable throughout this work unless otherwise specified. Examples of other CPA-related quantities include CPA bearing and time at CPA.

[3]In MOOS variables, the letter h denoted heading for ease of coding. Throughout mathematical

and velocities (v) were considered with respect to each other. The current contact's position was extrapolated along the contact's current course at the current speed using Equation 2.1 and compared to the extrapolated positions of own ship for all possible heading and speed combinations originating from the current own-ship position. A graphical example of this extrapolation is shown in Figure 2-5.

$$y_{c1} = y_c + v_c \cdot t_1 \cdot \cos(\phi_c) \tag{2.1}$$

The full positional extrapolation leading to the evaluation of CPA can be described mathematically using Equation 2.2 where k_2, k_1, and k_0 are the parametric coefficients for powers of time t^2, t, and constant coefficients respectively. These parametric coefficients are defined using Equations 2.3, 2.4, and 2.5 respectively for all possible contact and own-ship vehicle positions in time by considering all feasible heading and speed combinations for each vessel's decision space [8].

For each known contact, a solution of CPA range was found based on track information as discussed in Section 1.5.2. In the time parametric equations for CPA using k_i notation (Equations 2.3, 2.4, and 2.5), (x, y, v, ϕ) denote $(x - position, y - position, velocity, heading)_{own-ship}$ while (x_c, y_c, v_c, ϕ_c) denote the same for the target vessel. Candidate solutions for various heading and speed combinations were then minimized by projecting forward in all relevant time and finding the smallest range between projected vessel positions using Equation 2.2. This computation was performed four times per second on the vehicles which made for effective real time evaluation. Vehicle maneuvers involving changes of course and speed were considered to be sufficiently incorporated into this solution method by considering the relative changes to a vessel's track on a time scale much larger than a quarter second evaluation cycle.

contexts in this work, ϕ denoted heading and was equivalent in all aspects except name to h.

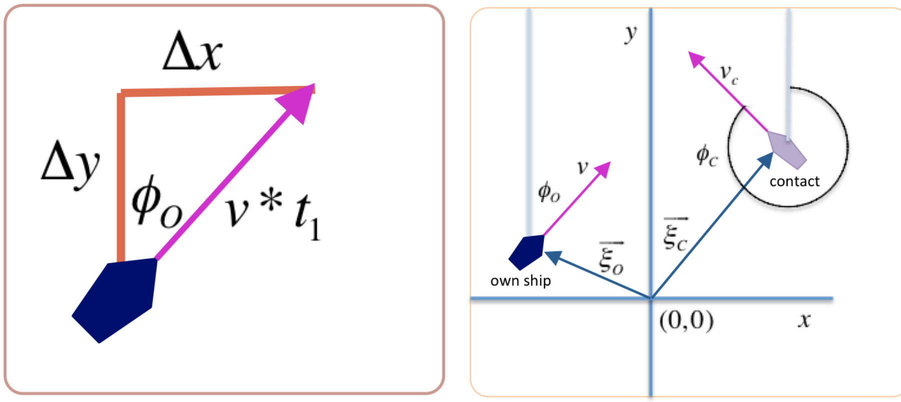

Figure 2-5: The trajectories of each vessel were allowed to continue in time according to the given heading (ϕ) and velocity (v). The point of closest range in all time was found using Equation 2.2 by finding the minimum range achieved between the two vehicles. In this figure, $\xi_c = (x_c, y_c)$ and $\xi_o = (x, y)$.

$$\begin{aligned} CPA &= f(x_c, y_c, \phi_c, v_c, x, y, \phi, v) \\ &= argmin_{time}[\sqrt{(x_c - x)^2 + (y_c - y)^2}] \\ &= argmin_{time}[\sqrt{k_2 t^2 + k_1 t + k0}] \end{aligned} \tag{2.2}$$

$$\begin{aligned} k_2 &= v^2 \cdot \cos(\phi) - 2 \cdot v \cdot v_c \cdot \cos(\phi) \cdot \cos(\phi_c) + v_c^2 \cdot \cos^2(\phi_c) \\ &\quad + v^2 \cdot \sin^2(\phi) - 2 \cdot v \cdot v_c \cdot \sin(\phi) \cdot \sin(\phi_c) + v_c^2 \cdot \sin^2(\phi_c) \end{aligned} \tag{2.3}$$

$$\begin{aligned} k_1 &= 2 \cdot v \cdot y \cdot \cos(\phi) - 2 \cdot v \cdot y_c \cdot \cos(\phi) - 2 \cdot y \cdot v_c \cdot \cos(\phi_c) \\ &\quad + 2 \cdot v_c \cdot y_c \cdot \cos(\phi_c) + 2 \cdot v \cdot x \cdot \sin(\phi) - 2 \cdot v \cdot x_c \cdot \sin(\phi) \\ &\quad - 2 \cdot x \cdot v_c \cdot \sin(\phi_c) + 2 \cdot x_c \cdot v_c \cdot \sin(\phi_c) \end{aligned} \tag{2.4}$$

$$k_0 = y^2 - 2 \cdot y \cdot y_c + y_c^2 - 2 \cdot x \cdot x_c + x_c^2 \tag{2.5}$$

By substituting the values of Equations 2.3, 2.4, and 2.5 into Equation 2.2, taking a partial derivative with respect to time, and equivocating to zero, the critical point for minimized range was found. The algebra then gives the time of CPA according to Equation 2.7 which can then be substituted into Equation 2.2 to give Equation

2.8. This value of CPA range found at the critical point in time was computed for all possible heading and speed combinations at a nominal frequency of four times per second.

$$CPA^2(\phi, v, t) = k_2 \cdot t^2 + k_1 \cdot t + k_0 \tag{2.6}$$

$$\frac{\partial}{\partial t}(CPA^2) = 2 \cdot k_2 \cdot t_{cpa} + k_1 = 0$$

$$t_{cpa} = \frac{-k_1}{2 \cdot k_2} \tag{2.7}$$

$$CPA(\phi, v, t_{cpa}) = \sqrt{k_2 \cdot t_{cpa}^2 + k_1 \cdot t_{cpa} + k_0} \tag{2.8}$$

2.4 Performance Metrics for Collision Avoidance

To properly analyze the collision avoidance algorithms, a set of metrics were first identified that could be used objectively across a spectrum of solutions. These metrics incorporated the two major considerations which are balanced with any manned or unmanned vessel's operations: safety and efficiency of performance. Safety for all vessels was of course paramount. While safety is non-negotiable for any normal vessel's operation, reducing the risk of collision to be a guaranteed value of zero without staying tied to the pier is impossible. By casting lines and going underway, all vessels inherently assume a risk of collision. The goal, therefore, of any captain or autonomous behavior controller is to achieve a desirable level of safety while balancing mission success. Often mission success of an ocean-going vessel is measured in a metric defined by odometer distance and time such as transiting a particular path within a given timeframe (such as a merchant) or traversing a particular track with as little deviation as possible (such as a surveying vessel). The similarity in these missions is that each focuses on balancing mission performance with mission safety while the former is subservient to the latter.

2.4.1 Safety

The metric for safety of collision avoidance considered finding the number of times a vehicle pair violated a nominal safety range as defined by a collision range ring and compared this to the number of waypoint legs that this vehicle pair interacted. The safety metric considered actual real time range between contacts and not CPA range. The following sections describe how a collision range ring was created, how violations were counted, and the difference between two major classes of maneuvers.

Collision Range Ring

Safety was the first metric considered for collision avoidance performance. To fully analyze safety, a method of quantifying how safe any two vehicles were with respect to each other was required. Based on the assumption of non hull-centered GPS receivers (see Section 1.5.2), the nominal collision range was defined as being the greatest possible range between these non-centered GPS receivers of two vessels in their most conservative collision geometry. An example of the non hull-centered GPS receivers is shown in Figure 2-6. For example, two vehicles with GPS receivers on their port sides were considered to be in a starboard-to-starboard collision scenario such that the GPS reported range at the time of their collision was equal to the sum of their beams as shown in Figure 2-7. This most conservative GPS-perceived range at time of collision was then scaled using a nominal safety factor and declared as the collision ring radius shown in Figure 2-8.

The final value for a nominal collision used in this work was set at three meters based on the dimensions of the M100 and M200 while accounting for the geometry shown in Figure 2-7 and adjusted for an additional safety factor. The more slender bodied M200 has a lesser beam as compared to the M100 in addition to a more hull-centered GPS receiver. For this reason, the limiting case for GPS-to-GPS reported range during an actual collision was the M100 vehicle pair. Additional studies performing collision avoidance as well as in-field adaptation of collision avoidance rules based on reported position must also take into account the range from the reported vessel position to the extreme point of structure.

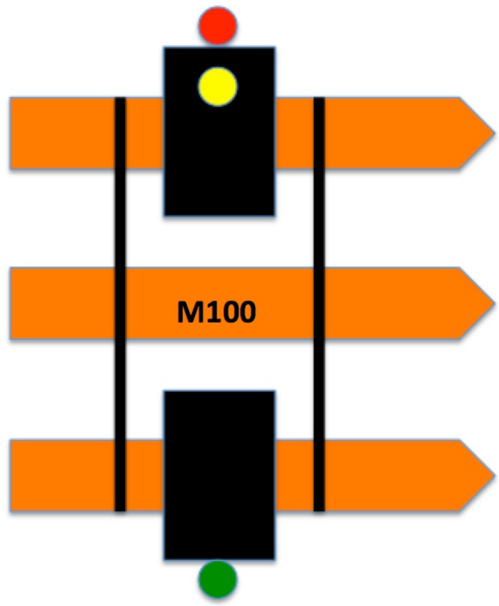

Figure 2-6: The M100 used a set of port (red) and starboard (green) running lights as well as a non hull-centered GPS receiver (yellow) located in the port computer housing.

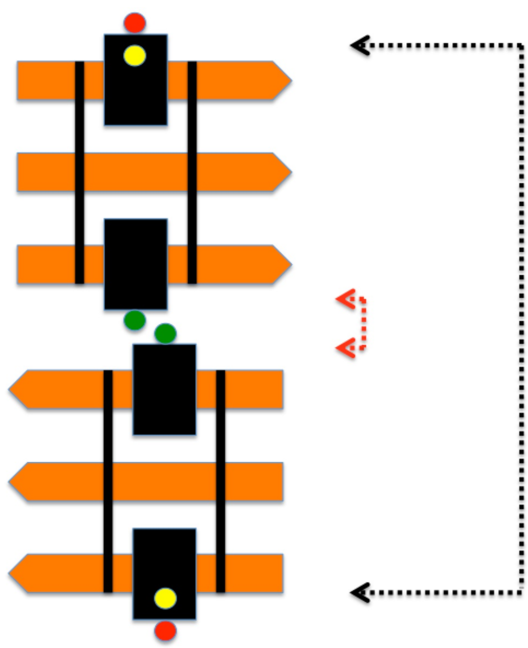

Figure 2-7: The most conservative M100 collision geometry for a vehicle pair occurred when non hull-centered GPS receivers were outboard each other. This distance plus a safety margin was used to compute a nominal range at which all lesser ranges were considered a collision. The black dimension marker along the right side denotes the calculated range based on reported outboard vessel positions. The red inner dimension markers denote the physical range between hulls.

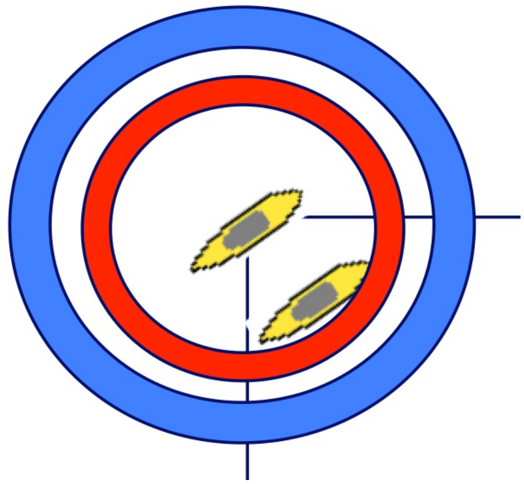

Figure 2-8: The collision ring was created for quantifying safety of any given vehicle pair. The red inner circle denotes the range at which a collision was considered to have occurred where the blue outer circle was the minimum desired CPA.

Number of Collisions

Safety was evaluated by first determining when any vehicle pair interaction resulted in a reported range less than the nominal collision range. The total number of collisions within the testing area could be counted for any length of evaluation. The total collisions could then be recorded and compared to the number of total vehicle pair interactions that occurred. A single interaction was defined as a vehicle pair activating a collision avoidance maneuver with another vehicle while en route to their next waypoint. The interaction would not be considered a subsequent interaction until the vehicles had reached their next waypoint. This allowed for an indefinite interaction time by discretizing their waypoints and using a simple yes/no scheme for whether any two vehicles interacted on a given leg. For example, if vehicle A and vehicle B interacted on 10 separate track legs while vehicle A and vehicle C interacted on 15 track legs, the total vehicle interactions would be 25. A violation of the collision ring for any pair (e.g., A and B, A and C, or B and C) was counted as a single collision event for the testing area regardless of which vehicles were involved. The metric for safety was defined as the ratio of the total number of vehicle pair collisions to the total number of vehicle pair interactions.

Symmetric and Asymmetric Maneuvers

Maneuvers of any two vehicles that result in active avoidance of each other are inherently dangerous if a protocol does not exist. A symmetric maneuver refers to an encounter which results in both vessels turning toward the same cardinal direction often resulting in an impending collision scenario. Any simultaneous maneuver by both vessels that results in a further decrease in range often results in a higher overall time rate of range closure. While a collision does not become requisite for an increased rate of range closure, the time available for the two vessels to negotiate a safe exit from the potential collision greatly diminishes. Examples of maneuvers that are symmetric and asymmetric are shown in Figures 2-9 and 2-10, respectively. Asymmetric maneuvers are therefore those which result in different cardinal headings for the two vessels. These maneuvers result in a greater CPA range and thus a more acceptable time rate of range closure.

2.4.2 Efficiency

Most marine vessels set a list of waypoints as incremental position goals in order to achieve the broader mission of the platform. For example, a merchant traveling from port A to port B will determine the most fuel efficient route and lay a series of waypoints to be achieved on their navigational chart. Similarly, a surveying vessel might be tasked with performing a lawnmower pattern to conduct acoustic mapping of a seafloor. In this work, efficiency was measured using odometer efficiency as discussed in the next section. A maneuver with reduced efficiency called a wrap-around is also discussed.

Odometer Efficiency

Regardless of the actual mission being achieved, any waypoint-based mission can be discretized into increments of successive waypoints by approximating the planned path as a series of piecewise linear segments. Measuring the actual distance traveled by a vessel was possible if real-time position was known with sufficiently small time

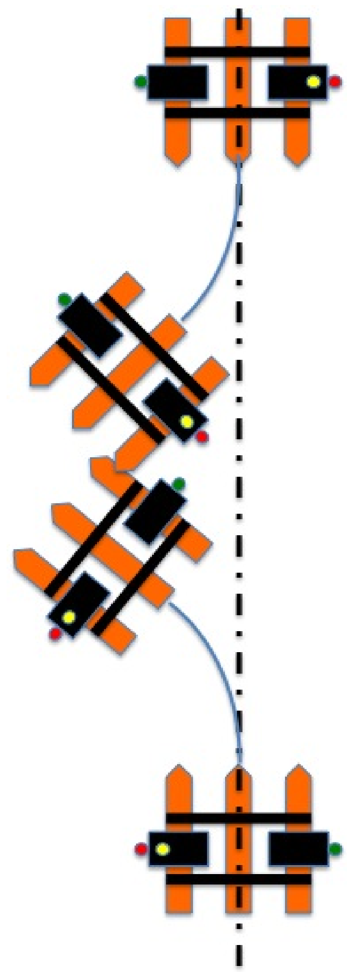

Figure 2-9: A symmetric maneuver results in a more drastic time rate of range closure than an asymmetric maneuver and is inherently avoided when operating in compliance with COLREGS.

intervals. With sufficient resolution of these time intervals, a total distance traveled could be computed and tracked as an odometer-like metric. This lead naturally to a metric for efficiency as the ratio of distances, or $\eta = \frac{d_1}{d_2}$, where d_1 was defined as the ideal travel distance between any two waypoints (i.e., the length of the line segment between the two waypoints) while d_2 was defined as the actual distance traveled as measured by an odometer using the vehicle's reported positions. Figure 2-11 shows the relationship of these two distances. The efficiency η was therefore fully defined on the domain of $(0, 1]$.

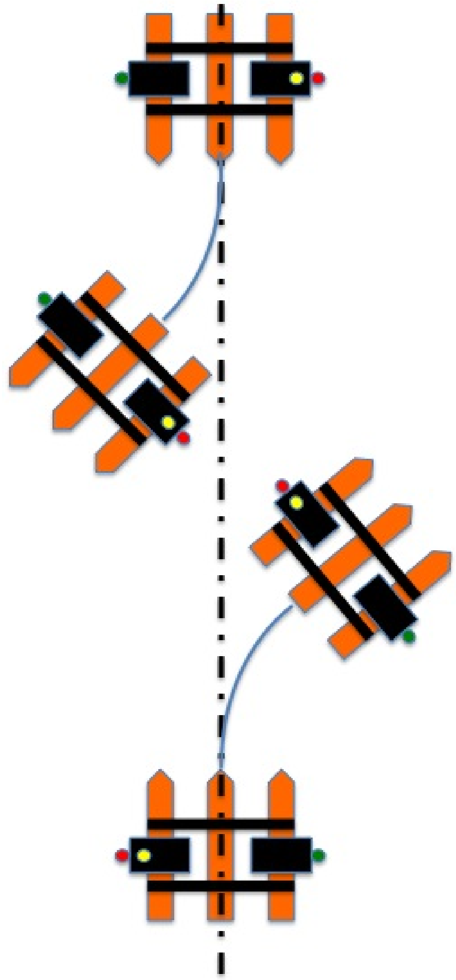

Figure 2-10: An asymmetric maneuver results in a safer outcome than a symmetric maneuver. By reducing the time rate of range closure and increasing the CPA range by using a protocol such as COLREGS, the resultant maneuvers if both vessels deviate course when avoiding a head on collision are guaranteed to be asymmetric as shown.

Wrap Around Maneuvers

Any maneuver that resulted in a full circular turn in either direction, or more practically, any maneuver that resulted in crossing one's own track within a specified distance traveled, was considered to be a wrap around. While this may be the safest maneuver in some extreme cases, it is never considered to be efficient or preferred. Wrap around maneuvers were indicative of a vessel maintaining its turn rate to drive a circle as a time wasting maneuver. Its global position remained nearly stationary while it allowed another vessel to pass. An example is shown in Figure 2-12.

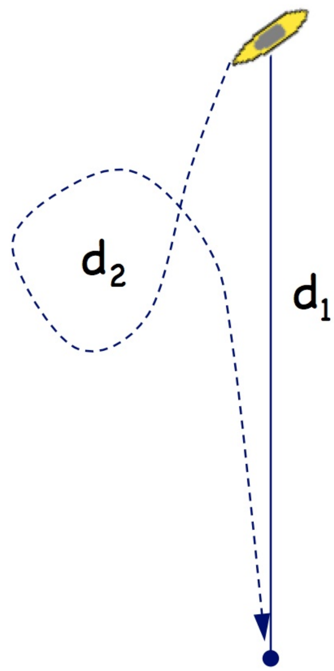

Figure 2-11: Efficiency ($\eta = \frac{d_1}{d_2}$) was determined by evaluating the ratio of ideal distance between waypoints (d_2) and actual distance traveled (d_1).

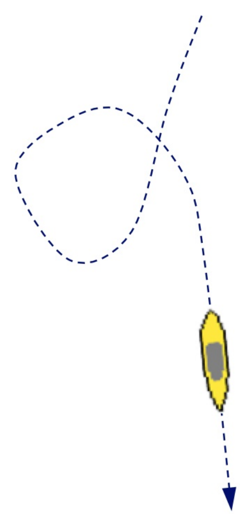

Figure 2-12: A wrap around maneuver was considered to have occurred if a vessel passed over its own track within a given distance of travel. This maneuver was considered inefficient, though in a constant turn to starboard, might indeed be a safer maneuver than other alternatives in a multi-contact avoidance situation.

2.5 Collision Avoidance Parameters of Interest

One area in which this research deviated significantly from other work in the literature was a study of how certain parameters within a collision avoidance decision space affected both the resulting safety and efficiency. By having a better understanding of how certain parameters affect both safety and efficiency, operators would be able to choose the values of collision avoidance parameters that satisfy the level of assumed risk of operation while maximizing the resulting efficiency. In determining how to illuminate the tradespace of collision avoidance for autonomous marine vehicles, five major parameters were studied. These parameters were essential to both the generic collision avoidance algorithm as well as the COLREGS algorithm[4] thus allowing for fair comparison, and they can also be easily extended to parameters experienced by operators of manned vessels. The three quantities used to derive the five parameters of interest were CPA range, current range, and speed. By knowing a contact's position, course, and speed as well as all possible combinations of own ship's position, course, and speed, a full solution of possible CPA ranges was attainable. By placing minimum and maximum values on both CPA range and instantaneous range, the total number of parameters became five: two for CPA range (*min_util_cpa_dist* and *max_util_cpa_dist*), two for range (*pwt_outer_dist* and *pwt_inner_dist*), and one for speed.

2.5.1 CPA Range Variables

CPA range was first determined as discussed in Section 2.3 then used to map all possible CPA range values to a more decision friendly quantity using a linear function between the threshold and objective CPA range values as realized by the variables *min_util_cpa_dist* and *max_util_cpa_dist* shown in Figure 2-13. By using the linear mapping, it was possible to declare all CPAs inside a threshold of *min_util_cpa_dist* as equally unfavorable as the CPA exactly at *min_util_cpa_dist*. Similarly, a mapping of all CPAs outside an outer threshold value of *max_util_cpa_dist* were considered equally as favorable as the CPA exactly equal to *max_util_cpa_dist*. By establishing these

[4]The generic and COLREGS algorithms are described in more detail in Chapter 3

criteria, the interval programming became much cleaner by declaring large regions of "good" and other large regions of "bad" with a transition interval between the two areas that was commensurate with the linear utility mapping of Figure 2-13.

This mapping would have been equivalent to a ship driver being given orders from the vessel's captain to take no contact within a certain range. By letting a contact within this threshold range, the ship driver would have violated the orders. It would have therefore been reasonable to say that any CPA within that prescribed range would be equally bad and assumed disastrous with zero utility. Similarly, a ship driver might have considered any CPA outside a threshold value to be considered equally as safe such that a larger CPA than this threshold distance would be considered merely inefficient rather than safer.

By analogy, a captain might have a preferred CPA range but will decreasingly tolerate closer CPA ranges down to the threshold CPA range.

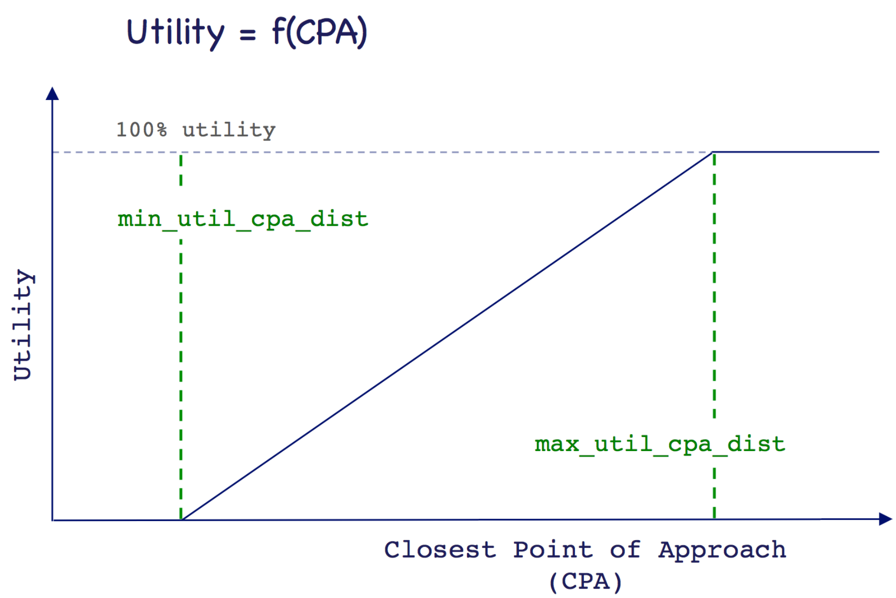

Figure 2-13: CPA was mapped to a utility value on [0,1] using a linear function. The two values for endpoints of this function were key parameters to this work. Graphic courtesy of [4].

2.5.2 Instantaneous Range Variables

Range was naturally considered to be an important factor for the helm as it would have been for any responsible ship driver. If a contact were distant but possessed an undesirable CPA range, it would seem reasonable to assign a watchful eye but not necessarily take drastic maneuvers to avoid an unfavorable CPA range until the contact grew closer. This could be reasonably justified by not knowing if the contact plans to deviate course in the great distance between the two vessels' then-present range or by further assuming that the contact solution will have finer resolution as the ship tracks progressed. One should also consider that a maneuver to avoid a very distant contact could be greatly unfavorable to mission accomplishment until an actual risk of collision existed further calling attention to the safety-efficiency tradespace. Finally there might very well have been other more important contacts at closer ranges that required higher priorities of attention for avoiding collision resulting in little to no relative weight being given to the distant contact. For these reasons, collision avoidance was set to consider the current range of each contact when considering the degree of priority to give to mitigating their collision risk through use of the *pwt_outer_dist* and *pwt_inner_dist* variables.

To determine the actual weight for the objective function of the contact avoidance behavior, a linear mapping was again performed based on contact range. Each vehicle's behavior file was assigned a positive weight for each behavior. For example, a waypoint traversing behavior might have been assigned a nominal utility value of 100 which would then be a baseline weight for any other behaviors that were active and thus producing objective functions to be evaluated by the IvP Helm. The actual weight w_i assigned to each behavior for evaluation as described in Section 2.1 was normally[5] this static number assigned in the behavior file. For the collision avoidance behavior however, this weight was the output of the utility function mapping the range to a priority weight shown in Figure 2-14. If a contact's range was therefore outside the *pwt_outer_dist* value, then the collision avoidance behavior spawned for that contact would have a weight of zero. Likewise, if a contact's range was equal to or less than the *pwt_inner_dist* value, then the behavior would have entered the solver

[5]Behaviors such as the waypoint behavior just completing basic traversal of a water space were given a static weight as to establish a relative baseline for behaviors with dynamic weighting schemes. Collision avoidance was an example of a behavior with a dynamic weighting scheme as it grew from no concern to grave concern as a contact became closer.

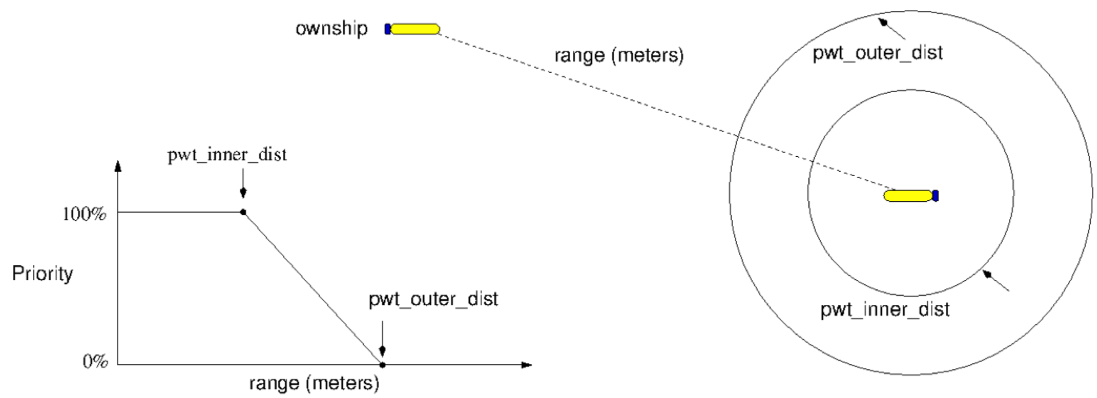

Figure 2-14: Current range to a contact was used in mapping the priority weight assigned to the collision avoidance behavior. The mapped value assumed the range of [0,max_utility_value] where max_utility_value was assigned by the operator. The nominal value for maximum utility was 300, or more generally, three times the weight of the primary mission. Graphic courtesy of [4].

with a weight equal to the maximum value for collision avoidance as assigned in the behavior file for each vehicle. The priority weight was mapped linearly between the two instantaneous ranges of interest. For the purposes of this research and consistent with most practice for autonomous marine vehicles of the size in this work, a nominal maximum weight for collision avoidance was set to be three times that of normal mission operations. This allowed for a balance to prevent frivolous course deviations while allowing extreme deviations from routine mission tracks when warranted for safety.

2.5.3 Relative Vehicle Speed

The final variable of interest to this regression analysis was relative vehicle speed. The tradeoff of interest for this variable was that a slower moving vehicle had a much smaller rate of range closure to other contacts, however, a slower vehicle was also less capable of quickly maneuvering to avoid a collision. Speed was inserted into the work as a nominal maximum speed for mission traversal and in no way mandated that a vehicle must achieve that speed at all times. Any speed between the assigned speed and zero speed was considered to be feasible for the solution space. For this work, multiple vehicles were assigned different maximum desired speeds at the launch of each experiment.

2.6 Evaluation of Performance Metrics

For the purpose of this work, two major outcomes were of interest to determine satisfactory implementation of COLREGS for autonomous marine vehicles: safety and efficiency. These two outcomes were used to quantify the relative improvement that was capable by autonomous marine vehicles operating with COLREGS as an alternative to a generic collision avoidance algorithm. By maintaining a vessel in a near-infinitely safe position, efficiency would be compromised. Similarly, by maintaining efficiency as paramount, safety would be neglected. A balance was sought to determine the combinations of collision avoidance parameters resulting in improved safety to an objective value of relatively collision free missions without grossly affecting efficiency.

The determination of how to rank safety and efficiency with respect to each other remains a choice of the operator charged with configuring an autonomous vehicle. Only this person would be able to determine the relative importance of safety and efficiency to the mission. One might consider two extreme scenarios to illustrate how the two factors must balance but would perhaps have varying degrees of importance. In the first case, consider a merchant transiting from Tokyo to Los Angeles carrying highly flammable cargo such as liquefied natural gas (LNG). This merchant certainly values efficiency to maintain costs as low as feasible, but when presented with a choice of making an unsafe maneuver to gain a slight increase in efficiency, one would expect that this operator would be risk averse. Maneuvering slightly earlier than another vessel might otherwise maneuver in order to open CPA range by an additional distance of comfort is most likely a highly attractive choice to this type of operator. Consider though a second case where a maritime patrol such as the Coast Guard is sending an autonomous vessel to intercept a suspicious boat over the horizon. This second operator is very much concerned with a fast and efficient trip, however cannot completely neglect collision avoidance. To do so might result in running into another vessel such as a large merchant that could have been easily avoided; however, this second operator is likely to assume significantly more risk than the LNG tanker of case one. Presumably there is some continuous tradespace between these two extremes that an operator might consider their desire for a high efficiency and weight that against their desire for overall safety. By evaluating the performance of these parameters, one can begin to see the significance of the tradespace that was examined in this work's design of experiments in Chapter 4.

2.6.1 Safety

For the purpose of the work, safety was quantified as a ratio of collisions to the number of vehicle encounters that occurred. A collision was defined as any reported range less than three meters as discussed in Section 2.4.1. The metric for safety was evaluated in both simulation and in-field testing by the shoreside server who was aware of all contacts and their positions using the uFldCollisionDetect tool discussed in Section 2.7.1. The final quantified metric was displayed as part of a summary chart for each test. An example of the safety portion of the summary chart is shown in Figure 2-15.

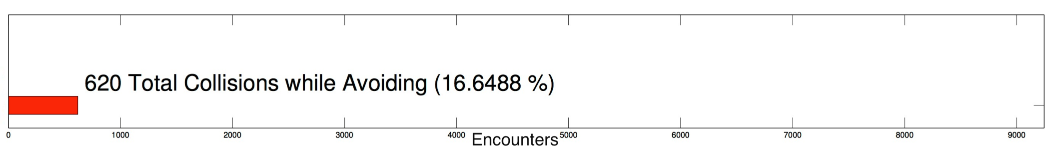

Figure 2-15: Safety was evaluated by determining the ratio of collisions to the number of transited legs that included an active collision avoidance behavior. Here a non-protocol collision avoidance test shows that 16% of all encounter legs involved a collision. The x-axis is scaled to meet the axis of the total encounter on the graph immediately below it as shown in Figure 2-20.

2.6.2 Efficiency

Track efficiency as defined and discussed in Section 2.4.2 was evaluated by finding statistical metrics for all data legs that were free of collision avoidance behaviors as well as all data legs that involved an active collision avoidance behavior. Figure 2-16 shows an example of graphical efficiency output from large data sets. The red histogram in the top chart of Figure 2-17 displayed an aggregate of all leg efficiencies that included at least one active collision avoidance behavior while the blue histogram on the bottom chart displayed an aggregate of all leg efficiencies that were free of any collision risk (i.e., no collision avoidance behavior was active during the entire traversal of the track leg). Statistics for the efficiencies such as mean, standard deviation, minimum efficiency, and maximum efficiency were determined for each experiment. Note that the example histogram showed a lower mean efficiency for legs requiring collision avoidance while it also displayed a more unpredictable outcome as depicted by the wider spread and higher standard deviation.

2.7 Tools for Quantifying Performance Metrics

To evaluate the metrics described in Section 2.4, several algorithms and tools required development. These were both for real-time evaluation during simulations and in-water testing as well as for post-mission analysis of the data logs. The real-time evaluation tools were integrated into the pMarineViewer (Section 2.2.1) for both real-time numerical output as well as graphical displays on the geospatial overlay. Of interest and thus of importance for development were tools to detect a violation of the collision range (uFldCollisionDetect), detect a wrap around maneuver (uFldWrapDetect), parse log files for efficiency information (alogeff), and analyze parsed efficiency information (various MATLAB tools) as described in the following sections.

2.7.1 uFldCollisionDetect

The uFldCollisionDetect tool was written for this research to detect violations of the nominal collision range of operating vehicles (either simulated or in-water) in real-time. This tool was integrated into each mission and was operated on the shoreside server to analyze position reports in real time for each vehicle. As each position report was received, each vehicle's position was compared to all other vehicles in the mission area. If any vehicle pair's range was determined to be less than that of the specified nominal collision range, a collision event was said to occur. This created a range pulse on the pMarineViewer screen which appears as a set of expanding concentric circles centered at the position of the collision. The visual cue was instrumental in alerting an operator to any problem that might not have been discernible from a close but non-colliding event. Further, a message was posted to the logs and text output of the pMarineViewer with the vehicle pair names, time, and distance from each other at the time of the occurrence. This proved instrumental in reconstructing collisions using logs post facto.

2.7.2 uFldWrapDetect

The uFldWrapDetect tool was written for this research and used to determine if a wrapping maneuver occurred as described in Section 2.4.2. This was recorded into the logs but did not warrant any special on-screen graphical warnings as it did not necessarily result in a particularly unsafe maneuver, but rather an inefficient case that warranted closer evaluation at a later time. These flags in the logs allowed an operator to quickly arrive back to the point of the occurrence to determine the vehicle's motivation for the particular decision of course and speed resulting in a wrap around maneuver.

2.7.3 alogeff

The alogeff tool was created for this research to analyze significantly large data files after missions were completed. Each vehicle created an asynchronous log "*.alog" file for each mission [26] that was run which recorded every command and status report generated from the start to the termination of the vehicle's mission. These files provided an unquestionably valuable view into the decision processes of the vehicles as well as their real-time environmental data that influenced those decisions. The alogeff tool was intended to be run on each vehicle to prevent transfer of large files.

With the extreme volume of information being stored to operate each vehicle[6], a tool was necessary to parse these files and filter them to only the applicable information required for post-mission processing of efficiency and safety. Full log files were

[6]The alog files generated during a single experiment of three vehicles and a shore side server for approximately 10^4 interactions would take approximately 200 GB of data storage space when only logging information essential to reconstructing the vehicle's history with respect to collision avoidance. The resulting files from alogeff for files of this size were approximately 0.5 MB.

maintained for reconstruction and analysis of any particularly interesting situations that were discovered. The full files also enabled a graphical "playback" of the mission as desired. The alogeff tool filtered the alog file for each vehicle and extracted an efficiency for each leg that was transited.

Alogeff further grouped these vehicle efficiencies by the type of leg that was represented: either a leg that was without any collision avoidance behavior being active or a leg that included at least one active collision avoidance behavior for another vehicle within the testing environment. The former was labeled as "transiting" legs while the latter was labeled as "avoiding" legs. These data points were recorded in their respective groups for later processing in post-mission analysis tools written in MATLAB. See Section 2.7.4 and Appendix A for a more detailed description of MATLAB tools written for this research.

In addition to vehicle log file processing, alogeff also processed shoreside alog files to extract key information on collision frequency. The shoreside files were parsed and filtered in a manner similar to the vehicle alog files. The variables of concern during shoreside alog file processing were related to actual collisions. At the completion of the alogeff tool being run on a shoreside alog file, a small file was generated with the number of collisions resulting from the mission.

All of the output generated from the alogeff tool was recorded in a way that was easily readable and usable by a MATLAB script. The post-mission analysis was then conducted in MATLAB using the filtered log files to examine only the variables and data of concern to the collision avoidance testing.

2.7.4 MATLAB Processing

Using a powerful mathematically driven software package for analyzing the post-collision avoidance mission data was instrumental to determining the outcomes of variation to key collision avoidance parameters. MATLAB was chosen to fulfill this requirement; several scripts were written to support the collision avoidance data processing and interpretation. The key to the MATLAB parsing was having a known input format from the alogeff tool. Of immediate significance was seeing statistical effects of large data sets as each of the parameters of interest were changed. The MATLAB scripts computed several statistical values of interest including mean, median, variance, minimum value, and maximum value for both transiting and avoiding efficiencies. The total number of collisions, percentage of collisions, and distribution of encounter type (transiting or avoiding) were also computed. All of this data was displayed graphically to give the shoreside operators feedback on the impact of changes to both safety and efficiency as a result of the permutations to the parameters.

To present an output that was both meaningful to and quickly interpreted by the user, a summary chart was created for each in-water test and simulation run that condensed statistical output of the test to include the safety and efficiency results. This chart consisted of four subplots including the two efficiency portions shown in Figure 2-17, the safety portion shown in Figure 2-15, and a distribution of data portion shown in Figure 2-18. This graphical representation of the distribution of data showed the proportion of transited legs that were analyzed with collision avoidance being active compared to those that were analyzed without collision avoidance being active. The final combination of the four charts were displayed uniformly for each output including printed statistical output to allow for quick analysis by operators. A syntactical layout of the graphical output is displayed in Figure 2-19 while an example of the graphical output in the final populated form is shown in Figure 2-20.

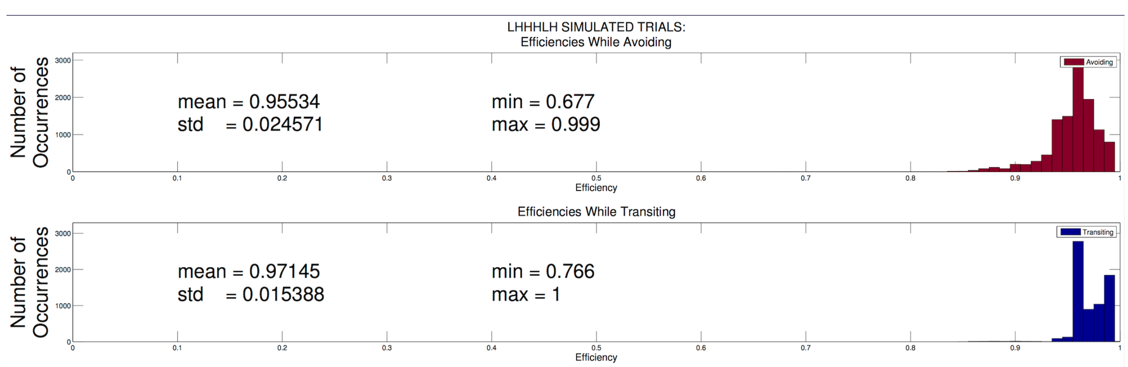

Figure 2-16: A chart displayed efficiencies to allow a broad view of how an experiment affected efficiency.

The charts were designed to express all data of interest to the operator in a single page. Of interest was a quick representation of how safe vehicles were for given

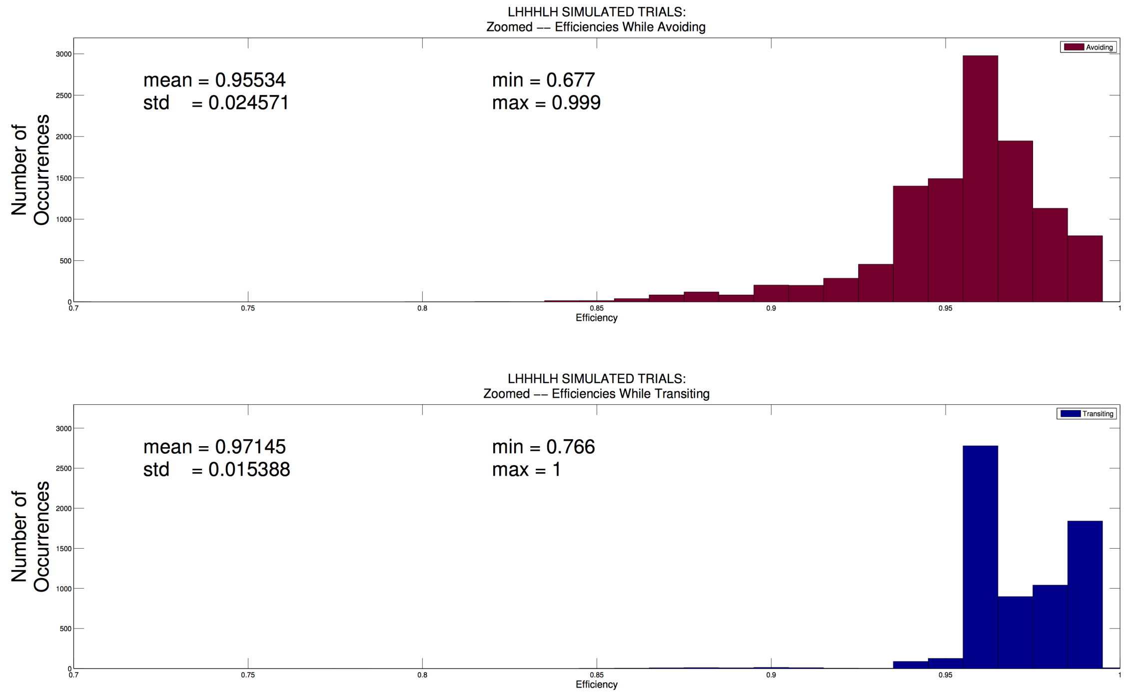

Figure 2-17: A second chart was created that zoomed in on the top 30% of efficiencies to allow a closer look at statistical shape in the region that contained the most interactions.

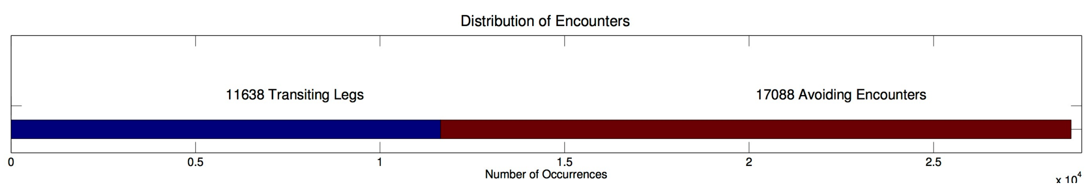

Figure 2-18: Graphical representation of the distribution of data to show the proportion of legs that were analyzed with active collision avoidance (right) and those that were analyzed without active collision avoidance (left).

parameters and how efficient these vehicles were under the same parameters. The efficiencies, safeties, and ratios of transiting and avoiding legs were shown using a series of histograms and bar charts. Specifically, the first and second of four subplots was a histogram of efficiencies within buckets of width equal to one percent increments. The top chart of Figure 2-20 in red represented all avoiding legs while the second chart in blue represented all transiting legs. Both of these two charts were normalized to show the same statistical significance while their vertical axes for actual number of occurrences were scaled appropriately for the normalization. The statistical quantities of interest such as mean, standard deviation, minimum, and maximum were output in numerical form and superimposed to their respective histogram. The third

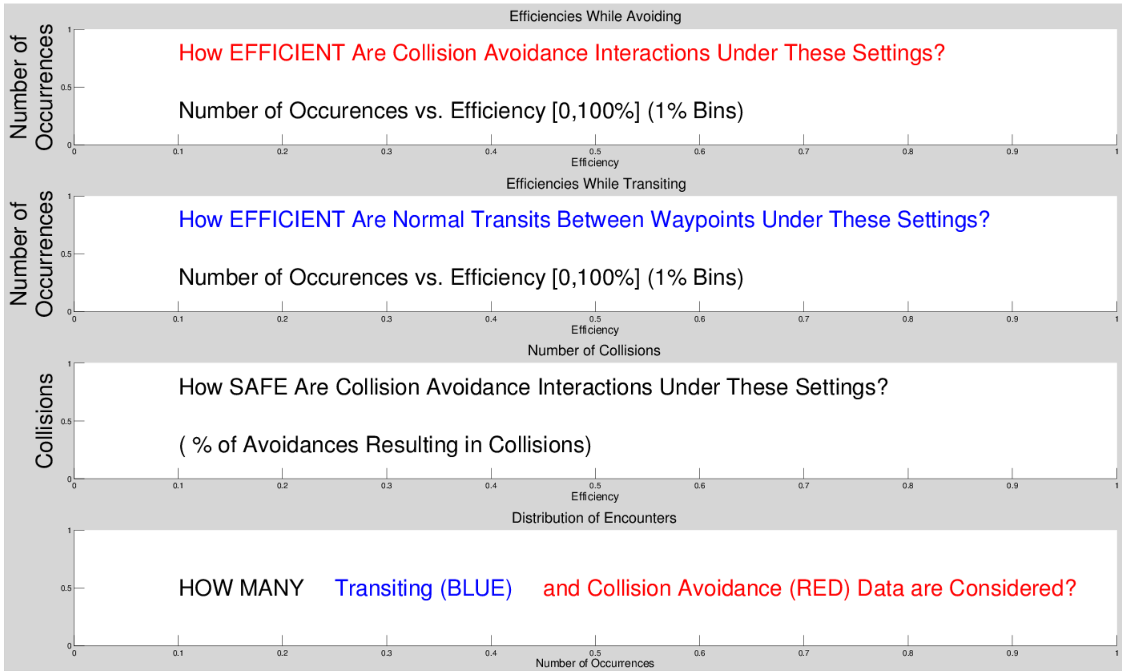

Figure 2-19: The MATLAB scripts computed several statistics of interest including mean, median, variance, minimum value, and maximum value for both transiting and avoiding efficiencies. The total collisions, percentage collisions, and distribution of encounter type were also computed. All of this data was displayed graphically to give the shoreside operators feedback on the impact of changes to both safety and efficiency as a result of the permutations to the parameters of interest.

subplot represented the number of collisions divided by the number of avoiding legs and was normalized by the number of avoiding legs. The fourth subplot represented the bar graph showing transiting (blue) and avoiding (red) legs both graphically and numerically so that the operator could quickly tell if the experiment was dominated by one type or the other.

Further details of the processing completed in MATLAB is found in Appendix A.

2.7.5 uLogView

The uLogView tool was included in the MOOS-IvP package and proved invaluable to analyzing logs in both simulation and real world experiments. The tool reads in the alog files then regenerates the top down view of what happened allowing a user to step through history at the appropriate time scale while graphically viewing the values of various numerical parameters that were recorded including the specific collision avoidance mode that were being executed at the time. These values were

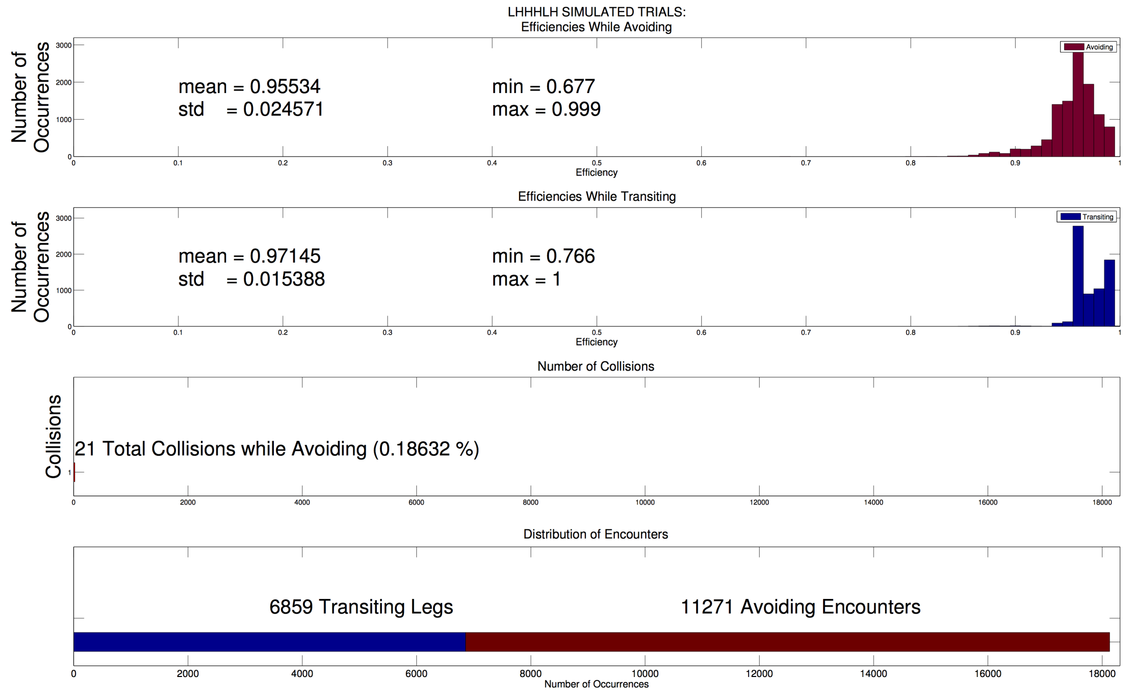

Figure 2-20: The graphical output for each test was displayed similarly using a four-part chart which included efficiencies of collision avoidance legs, efficiencies of non-avoiding legs, safety of the overall test, and the distribution of collision avoidance and non-collision avoidance legs.

displayed against time along the bottom of the tool's display. This proved invaluable for debugging as well as for the robustness testing and edge case search that allowed for high assurance of being in the correct rule while appropriate. An example of uLogView is shown in Figure 2-21 for an experiment run on the Charles River.

2.7.6 uLogViewIPF

The uLogViewIPF tool was included in the MOOS-IvP package and allowed the user to view the active objective functions in synchronous with the uLogView display. The user could select between a single objective function and the overall objective function to determine what was influencing the vehicle's behavior and how it might be improved. An example of uLogViewIPF is shown in Figure 2-22 in both 2D and 3D. The ability to rotate an image often proved highly useful to see what the vehicle desired for course and speed.

In Chapter 3, the algorithms for collision avoidance are presented including the application of the aforementioned parameters, tools, and evaluation techniques to the

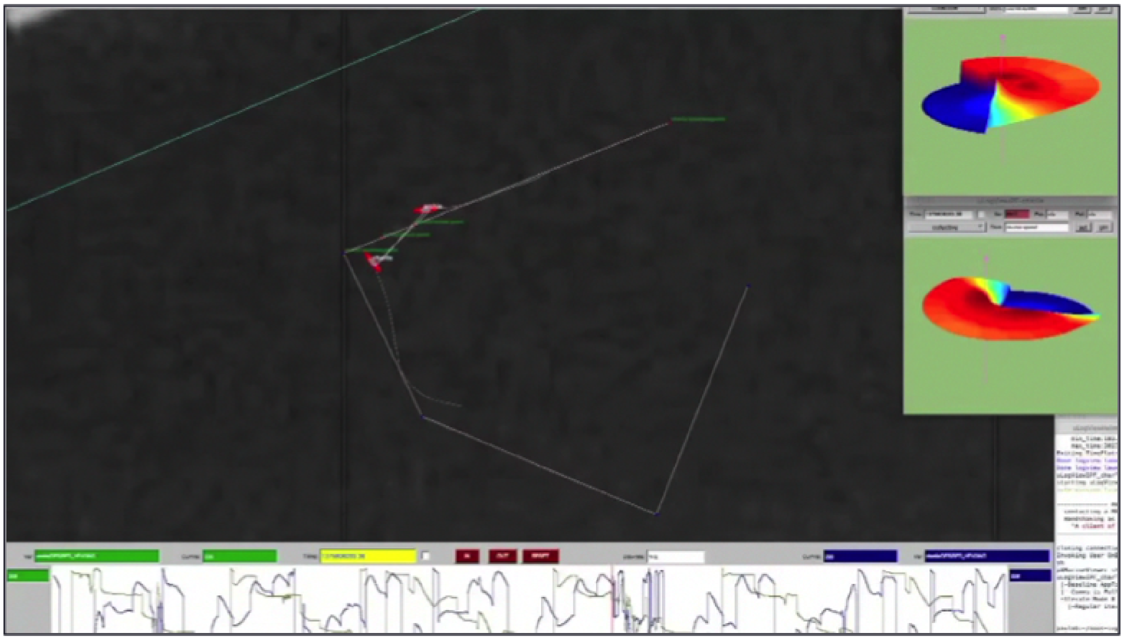

Figure 2-21: The uLogView tool was included in the MOOS-IvP package and proved invaluable to analyzing logs in both simulation and real world experiments. This image was of a actual experiment on the Charles River that underwent reconstruction of logs. The polar plots on the right represent the collective objective functions of each vehicle while selected variables are displayed against time along the bottom of the graphic.

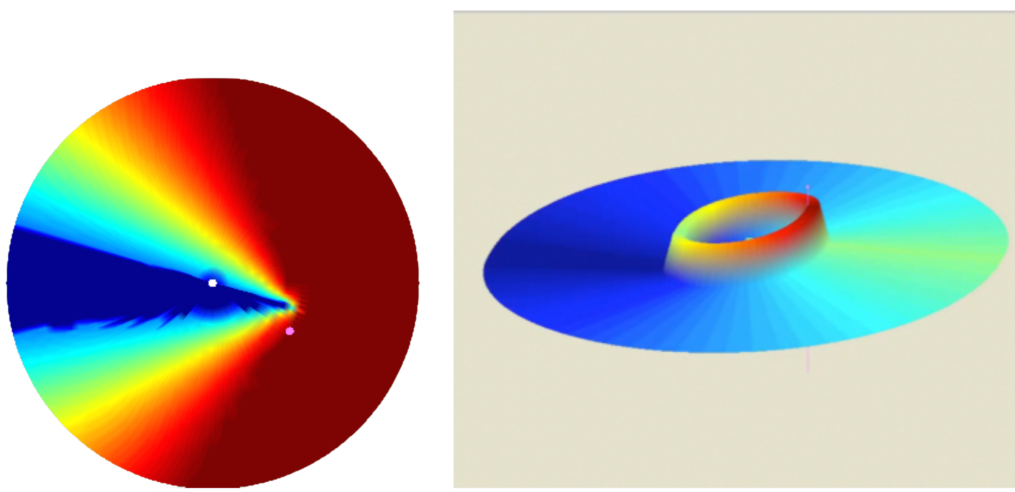

Figure 2-22: The uLogViewIPF tool was included in the MOOS-IvP package and allowed the user to view a single objective function or the overall objective function to determine what was influencing the vehicle's behavior and how it might be improved. In this polar representation, the polar angle represents heading ϕ while the radius represents the velocity normalized between zero and maximum possible decision space velocity. Here, the left graphic shows a nominal top down view while the right graphic shows a rotated view to demonstrate the correlation between color and objective function value where red is high value (approaching 100) and blue is low value (approaching 0).

development, robustness testing, and experimentation of autonomous marine vehicles.

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Chapter 3

Collision Avoidance for Autonomous Marine Vehicles

3.1 Overview

Chapter 1 demonstrated the importance of having a properly functioning collision avoidance system either as a human operator or an automated system to prevent collisions at sea. Chapter 2 described the methods used to test COLREGS on autonomous marine vehicles to include the software, AMV platforms, geometries, metrics, and tools. This chapter discusses the approach for autonomous collision avoidance algorithms as well as the results of both in-water and simulated testing including a discussion of in-water testing performed with five autonomous marine vehicles concurrently. The approach and results derived from the design of experiments with regression analysis will be discussed in Chapter 4.

3.2 Two Approaches to Collision Avoidance

Collision avoidance algorithms may be coarsely divided into two major types. The first type is an ad hoc system of avoidance that runs on an individual platform with either no ability to communicate or no pre-established protocol for behavior. These systems are referred to as non-protocol based collision avoidance algorithms and include behaviors that are purely CPA based as well as emergency backdown behaviors discussed in Section 1.4. The second type of collision avoidance behavior is the type that either allows for communication or has a pre-established description of expected behavior. These more predictable collision avoidance behaviors are referred to as protocol based algorithms and include COLREGS which inherently act as a protocol for all operators abiding by the Rules.

3.2.1 Generic Non-Protocol Collision Avoidance Behaviors

The first collision avoidance approach analyzed in this study was the standard behavior used in the MOOS-IvP realm for autonomous marine vehicles operating in non-solo operations, namely the BHV_AvoidCollision behavior. This algorithm was designed with safety in mind but takes account only for ownship's efficiency rather than considerations for improvement to the collective vehicle efficiency resulting from protocols. When using this collision avoidance behavior, many vehicles experienced maneuvers that avoided collisions but resulted in highly inefficient track deviations. Further, symmetric maneuvers [1] often resulted from this behavior's course and speed decisions which always led to a closer range with a pointing aspect between contacts. An awkward dance-like encounter was often witnessed which very much resembled the last minute shuffle one might encounter while walking in a hallway where two people traveling in opposite directions were not paying attention until the last moment resulting in several rapid changes of direction in the same cardinal direction without immediate resolution as to how safe passage would be accomplished. Two typical examples of inefficient maneuvers that resulted from the generic collision avoidance behavior are shown in Figures 3-1 and 3-2.

In short, this type of behavior was greedy, not based on any protocol, and had very limited scalability. The greediness comes from the tendency to seek a solution that was best for the individual vehicle while neglecting entirely a maneuver which would have equivalent benefit for own-ship with potential improvement to global efficiency of the vehicle collective. This was mostly a result of having a non-protocol based solution

[1] Symmetric maneuvers are discussed in detail in Section 2.4.1

Figure 3-1: In this example, an AMV deviates from course much more than necessary to avoid a collision due to an inefficient and unsafe symmetric maneuver by the second AMV.

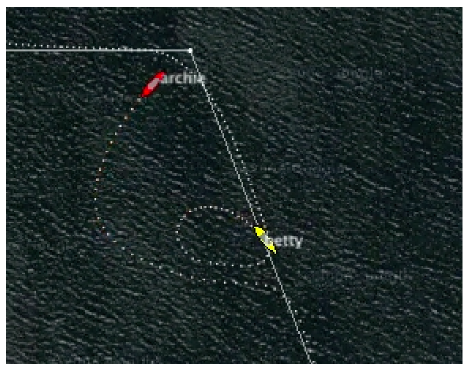

Figure 3-2: In this example, an AMV deviates from course much more than necessary to avoid a collision due to its own inefficient and unsafe symmetric maneuver. The second AMV takes action to avoid a collision resulting in a wrap-around maneuver.

for collision avoidance. In an environment where direct communication with a contact is unavailable other than position, course, and speed similar to what a captain of a manned vessel would have simply by his or her own radar, a protocol-based system results in knowing the likely maneuver of other contacts within the environment. These problems were only amplified as the contact density was increased resulting in higher collisions and greater loss of efficiency.

3.2.2 Protocol-Based Avoidance with COLREGS

The second approach to collision avoidance for autonomous marine vehicles operating using the MOOS-IvP architecture was constructed and named BHV_AvoidColregs by incorporating the protocols in COLREGS [1]. The protocols and specific language of the rules are discussed in Section 3.3 as part of a general overview of the geometries of concern for collision avoidance.

The most important aspect when considering a collision avoidance algorithm was its scalability to being used uniformly throughout the world by both manned and unmanned vessels alike. This scalability drove many design decisions including allowing many of the parameters to be configurable to the operator. The sensitivity and impact of these variables were the focus of the design of experiments portion of this study discussed in Chapter 4.

By simply converting the collision avoidance of AMVs to a protocol-based system, the need for communication other than knowing position, heading, and velocity was eliminated. With these parameters known and the operator's configuration values passed at the time of the underway, the autonomous vessel was completely empowered to make appropriate decisions regarding collision avoidance.

What was shown to be sometimes difficult using the non-protocol collision avoidance algorithm such as the head on scenario of Figures 3-1 and 3-2 was immediately improved to a consistent and safe passing as shown in Figure 3-3. Further analysis of the specific algorithms and their outcomes are shown throughout the remainder of this Chapter.

3.3 COLREGS Algorithms for Power-Driven Vessels

Three principle geometries were considered throughout this study for this collision avoidance strategy for autonomous marine vehicles: overtaking, head on, and crossing. These three geometries coincided primarily with Rule 13 (overtaking), Rule 14 (head-on), and Rules 15-17 (crossing) of COLREGS, while not excluding the importance and inherent simultaneous (and sometimes superseding) requirements of other rules within COLREGS. Because these three rules are the main drivers for conduct of

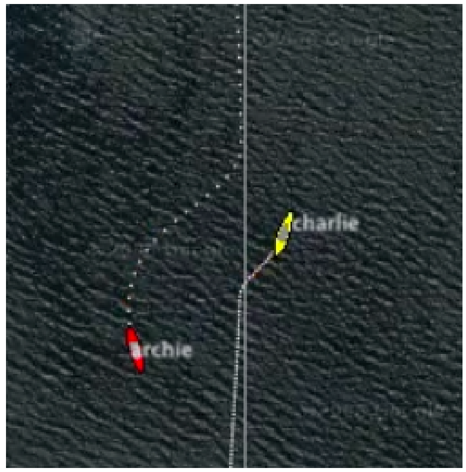

Figure 3-3: Two AMVs approach each other similar to the approaches of Figures 3-1 and 3-2. With COLREGS, the avoidance was much more safe and efficient as seen by reduced track deviation and a lack of either vessel pointing the other after the maneuvers begin. Note the smaller track deviation characteristic of the slower vehicle.

vessels within sight of each other assuming both are power-driven, they were chosen to be the primary focus of this study. These three major geometries are shown in Figure 3-4.

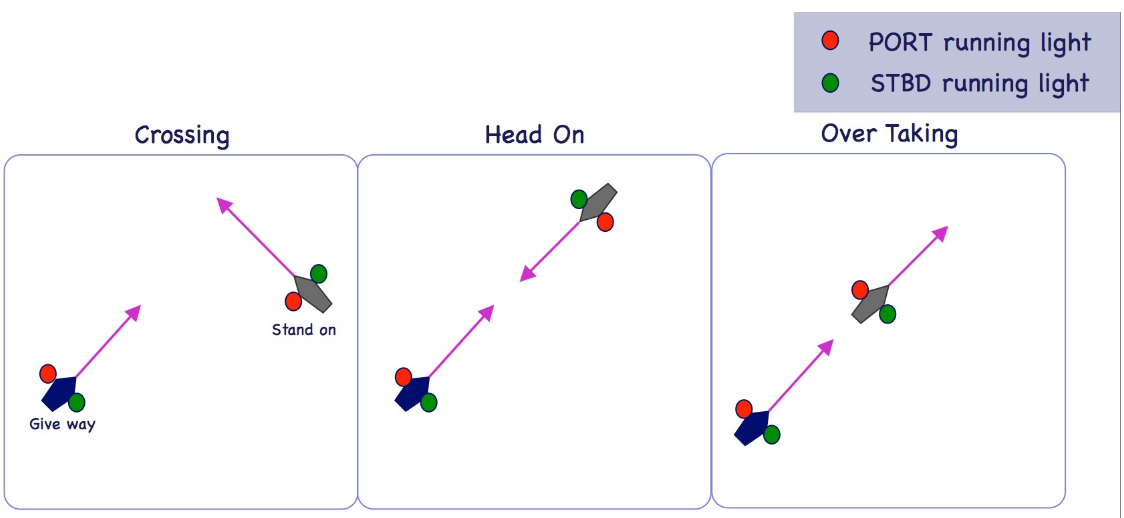

Figure 3-4: The three collision avoidance geometries of concern include the crossing, head-on, and overtaking situations. Overtaking situations are described in Rule 13; head on situations are described in Rule 14; crossing situations are described in Rules 15-17.

3.3.1 Overtaking

Overtaking is defined in Rule 13 of [1] as stated below. The short explanation of this rule is that any vessel that is overtaking another (as defined by specific geometry and relative speed) must do so safely and stay out of the overtaken vessel's way at all times.

The overtaking algorithm of this research accounted for the necessity of a decision regarding the side of the contact vessel to be overtaken. To avoid thrashing behaviors where the vessel might attempt a port passing then change to a starboard passing, a decision on the side to be overtaken was analyzed and that decision was enforced without change until rule was resolved resulting in no thrashing behavior. To decide on which side of the contact the vessel would overtake, the trajectory was analyzed to determine if the vessel would benefit from a port or a starboard crossing as well as whether crossing the contact's track would occur fore or aft of the contact. In an event that overtaking situation could be resolved by simply crossing the stern of the vessel and continuing without a risk of collision (and thus without necessity of being in the overtaking rule) that option was executed. For more standard overtaking geometries, the most sensical side was selected and an appropriate course and speed combination was ordered to respect the operator's pre-programmed desired CPA domain discussed in Section 2.5.1.

An example of the objective functions in polar form are shown in Figures 3-5 and 3-6.

> RULE 13: Overtaking (International / Inland)
>
> (a) Notwithstanding anything contained in the Rules of Part B, Sections I and II, any vessel overtaking any other shall keep out of the way of the vessel being overtaken.
>
> (b) A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is

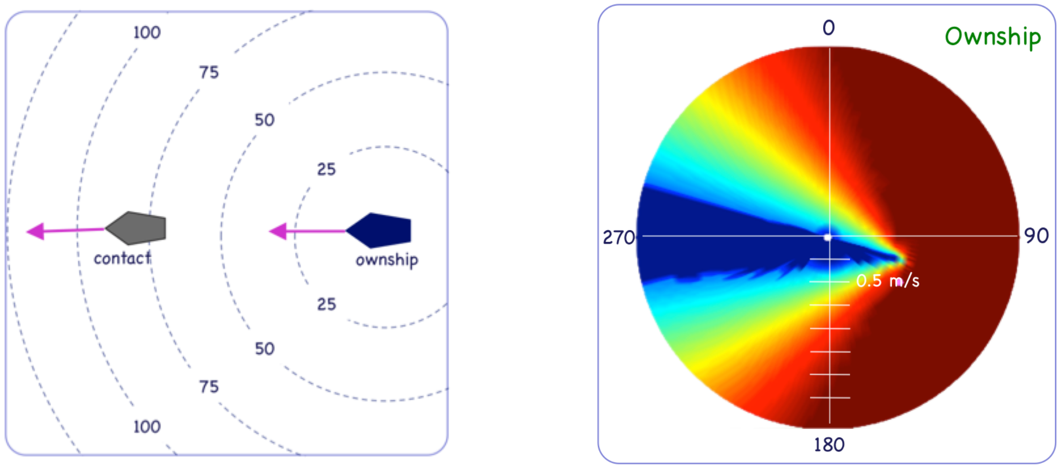

Figure 3-5: The objective function for the generic algorithm approach of overtaking is shown. Note that turns to South or North were both acceptable resulting in the possibility of thrashing if a slight deviation causes the opposite side to suddenly become incrementally better than the current side.

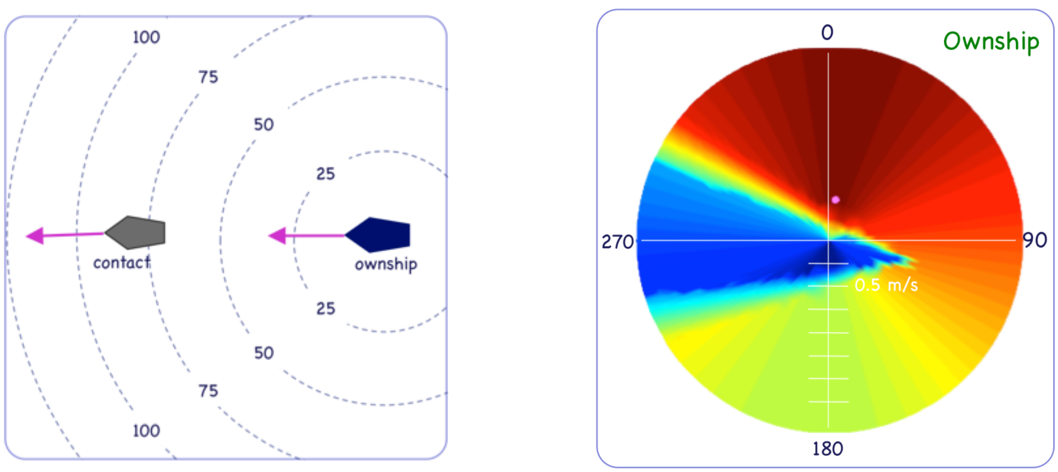

Figure 3-6: The objective function for the COLREGS algorithm approach of overtaking is shown. Note that the turn to South has been strongly discouraged once the initial choice of a port-side overtaking was decided.

overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.

(c) When a vessel is in any doubt as to whether she if overtaking another, she shall assume that this is the case and act accordingly.

(d) Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear.

3.3.2 Head On

The head on situation was defined in accordance with the Rule 14 of COLREGS [1]. A head on scenario is most easily described as two vessels approaching each other on nearly reciprocal courses such that they might intermittently see (or almost be able to see) both the port and starboard running lights of the contact in question. A head on scenario was the basis for significant problems resulting from symmetric maneuvers in the generic non-protocol based collision avoidance algorithm.

Within this research, the head on behavior allowed for much latitude for vehicles to maneuver within the desired CPA ranges so long as the requirements of the COLREGS rule was enforced.

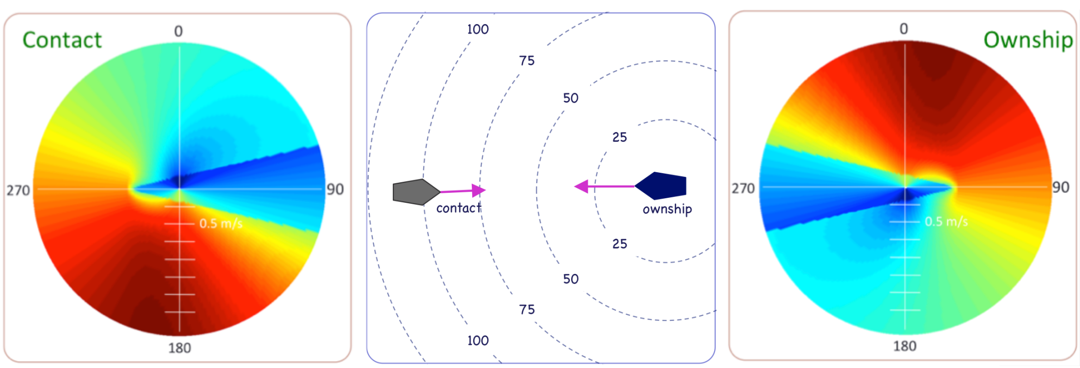

Figure 3-7: The objective function for the COLREGS algorithm approach of head on is shown. Note that the turn to port (shown as cardinal North for the left graphic and cardinal South for the right graphic) has been heavily penalized almost to the same degree as driving into the contact. This image shows that the two vehicles were highly encouraged to each turn to starboard and continue their track in accordance with Rule 14.

RULE 14: Head-on Situation (International: (a) through (c) only; Inland: (a) through (d))

(a) When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

(c) When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly.

(d) (Inland Only) Notwithstanding paragraph (a) of this Rule, a power-driven vessel operating on the Great Lakes, Western Rivers, or waters specified by the Secretary, and proceeding downbound with a following current shall have the right-of-way over an upbound vessel, shall propose the manner of passage, and shall initiate the maneuvering signals prescribed by Rule 34(a)(i), as appropriate.

3.3.3 Crossing: Give Way and Stand On

The term “crossing” is a generic term that has a very specific meaning within the context of COLREGS. Rule 15 defines crossing to be two vessels whose tracks will cross with a risk of collision. Rule 15 then assigns a role to each of the two vessels depending on geometry and requires each of these two vessels to enter the appropriate rule. For the vessel who sees the other vessel’s port (red) running light, the vessel is considered to be the give way and must take appropriate action per Rule 16. The vessel who sees the other vessels starboard (green) light is the stand on vessel and is required to take action per Rule 17. These three rules are required to all be active at once, i.e., Rule 15 defines which vessel is which, and Rules 16 and 17 delineate their respective actions. Therefore, the term "crossing" in the context of this research referred to the collective of Rules 15, 16, and 17 and their interdependent requirements for execution of safe maneuvers. Of note, Rule 17(a)(ii) gives the stand on vessel the authority and responsibility to take action to avoid collision before the give way vessel takes action in cases of the vessels being in extremis. The requirement of Rule 17 (c) to never turn to port was often violated in other COLREGS-like research presented in Section 1.4 but was enforced in accordance with the rules in this work [28]. The crossing objective functions are shown in Figures 3-8 and 3-9.

RULE 15: Crossing Situation (International: paragraph (a) only; Inland: paragraphs (a) and (b))

(a) (International / Inland) When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

(b) (Inland only) Notwithstanding paragraph (a), on the Great Lakes, Western Rivers, or water specified by the Secretary, a power-driven vessel crossing a river shall keep out of the way of a power-driven vessel ascending or descending the river.

RULE 16: Action by Give-way Vessel (International / Inland)

(a) Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

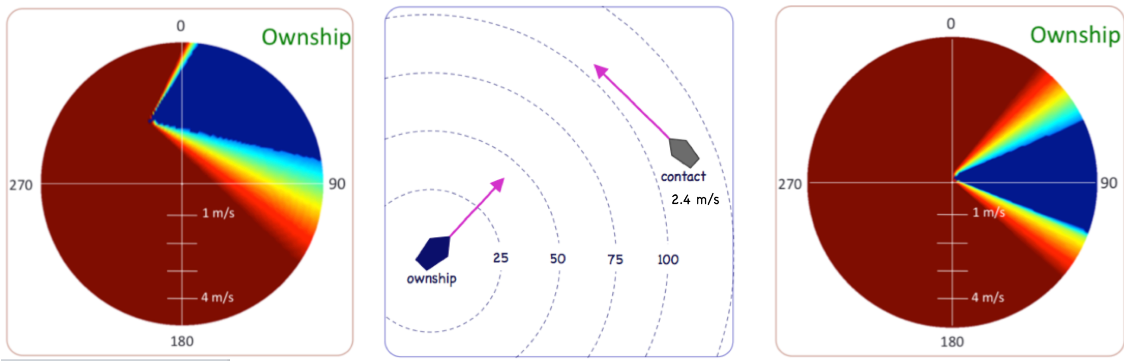

Figure 3-8: The objective function for the COLREGS algorithm approach of give way crossing is shown. The image on the left shows the objective function that prevents a vessel from normally crossing a contact's bow in accordance with Rule 16. The image on the right shows the objective function that allows a vessel to cross the bow of a contact who is slow moving and thus has a negligible risk of collision.

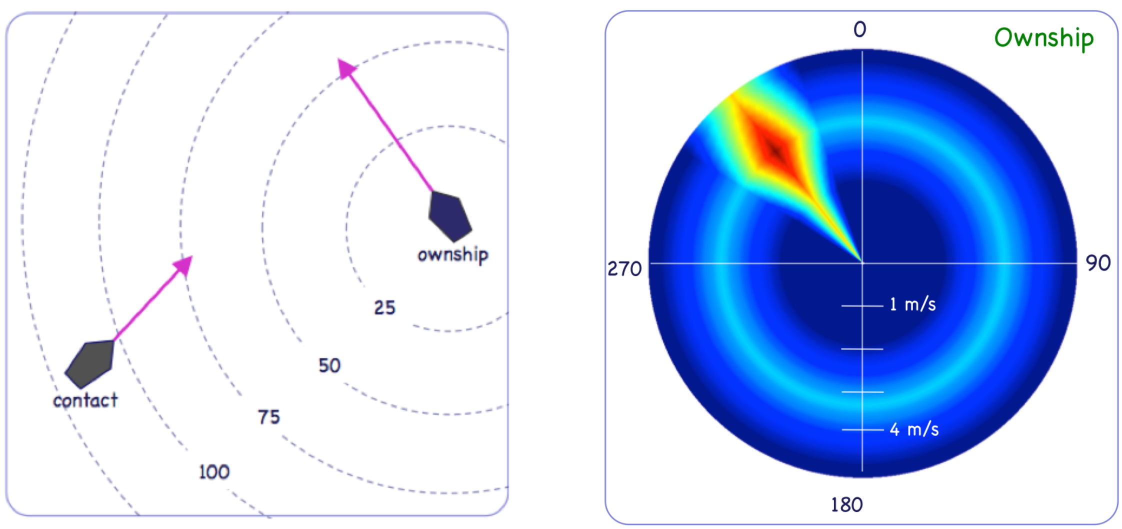

Figure 3-9: The objective function for the COLREGS algorithm approach of stand on crossing is shown. The objective function shows that there was a high desire for maintaining course and speed. The contact was continuously evaluated to allow a change to the objective function for evasive action to starboard in the case of a negligent give way vessel causing the two vessels to become in extremis.

> RULE 17: Action by Stand-on Vessel (International / Inland)
>
> (a)(i) Where one of two vessels is to keep out of the way the other shall keep her course and speed.
>
> (a)(ii) The latter vessel may however take action to avoid collision by her maneuver alone, as soon as it becomes apparent to her that

the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.

(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power-driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

3.4 Bounding of Simulation Limitations

Before conducting long duration simulations, it was necessary to determine the sensitivity of the simulation environment to faster-than-real-time speeds. These accelerated simulations are known as time warp within the MOOS-IvP environment. The importance of this verification was to find a reasonably fast simulation speed without compromising the integrity of the simulations themselves. In real world on-water experiments, the equivalent time warp was equal to one. To allow for long duration simulations of each configuration parameter combination, different warp values were used until no significant change in long term statistics were seen. Further a comparison of a normal build of the system software compared to a release-specific build was conducted. The result of this testing showed that a conservative time warp value of 5 times real-world speed allowed for a reasonable gain in processing time without affecting long term statistical values of collision frequency or efficiency using a release-specific build of MOOS-IvP. For comparison, warp values near 30 times real-world speed incurred a tripling of collision percentages compared to real-time simulations.

The reasoning behind the increased collisions was believed to be that the CPA calculations occurring at 0.25 Hz (nominal value and scaled appropriately for warped times) could not be fully computed in warps significantly higher than 5 resulting in incomplete and lagged information being used to compute helm decisions. A warp value of 5 allowed for sufficient computation margin for the high speed simulations as shown by no change in long term statistical values for a given set of collision avoidance configuration parameters.

3.5 Results of Testing

Tests were performed on both real autonomous marine vehicles and simulated platforms. In each case, the exact same behavior code was used with the only difference being whether true GPS and motor control signals were used as in the in-water experimentation. All reactions and IvP decisions were made in the same fashion with no regard for how the GPS information was obtained.

3.5.1 Simulated Tests

To ensure uniformity of results, simulation testing was performed on machines running Mac OS with MOOS-IvP. During simulations, the machines were dedicated entirely to the experiments with no extraneous processes running. A detailed analysis of the results for simulation is presented in Section 4.5.

3.5.2 Robustness Testing

The robustness of the collision avoidance algorithms was tested using multiple approaches. The first aspect of ensuring a robust solution was to ensure that multiple rules could be handled simultaneously. To test this, a home plate-like course was used to allow for multiple angles of encounter with three vehicles traveling at multiple speeds. This scenario allowed for simultaneous head on, overtaking, and crossing scenarios. The randomness resulting from long duration simulations ensured that an appropriate amount of non-canonical encounter angles were experienced resulting from compounding rules as well as incomplete recovery to intended track prior to another encounter. An example of the track as well as the compounding geometry is shown in Figure 3-10.

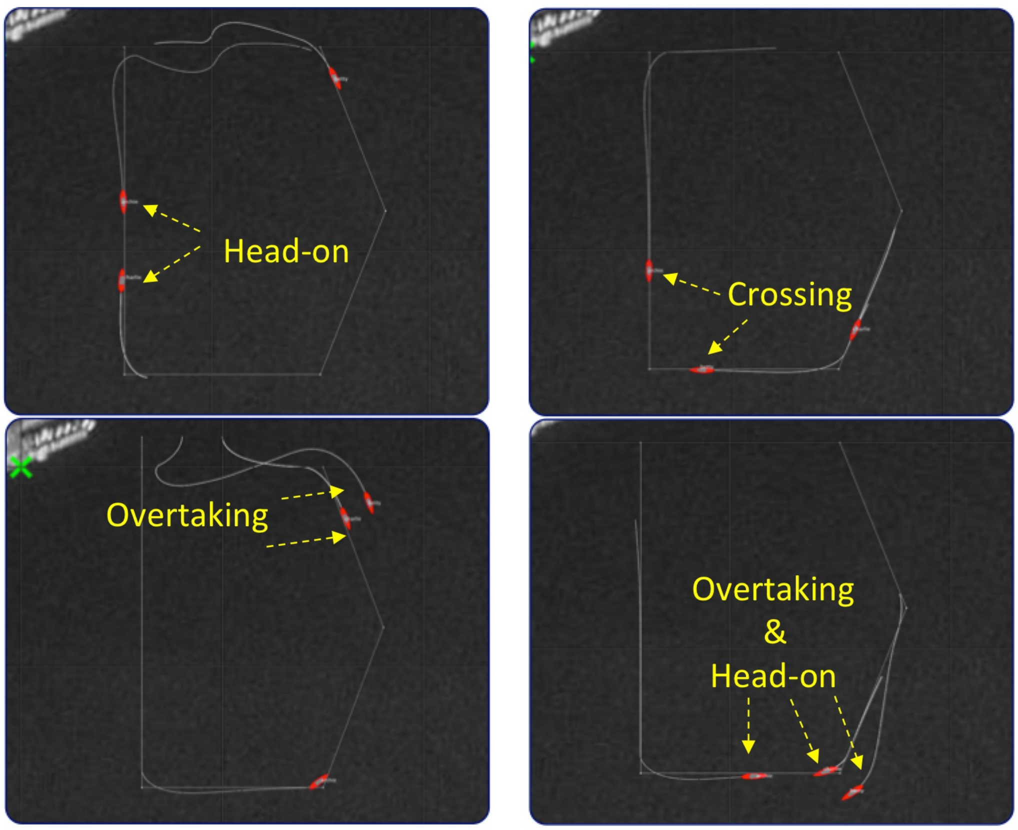

Figure 3-10: Robustness testing was first tested using the home plate course shown. This course allowed for multiple rules to be active simultaneously with multiple contacts. Other features included non-canonical course angles as well as resulting non-canonical angles from incomplete returns to track prior to a subsequent collision avoidance encounter.

To robustly test many crossing scenarios to ensure proper stand on and give way compliance, a course was established using a north-south vessel and an east-west vessel. Each vessel had a loiter polygon at the extreme coordinate, for example at the extreme eastern part of the course followed by the extreme western part of the course. The vessel would loiter in its assigned polygon until permuted, then the vessels would attempt to switch from east to west and from north to south. The locations of the polygon locations within the extreme sides varied on each iteration. For example, the eastern polygon would always appear in the east, though it would change locations to be slightly different than previous iterations to ensure varying encounter geometries and timing. After a repeated number of permutations, a slow motion review to include analysis of when vehicles deemed themselves to enter a collision avoidance rule was conducted. This robustness testing proved invaluable for fine tuning and ensuring robust entry and exit criteria for the stand on and give way rules. An example of the geometry used including the loiter polygons for the test are shown in Figure 3-11.

Figure 3-11: Two vehicles alternated between North-South and East-West polygons. These polygon positions were randomly positioned ensuring that each permutation resulted in a new geometry and timing. The results were then examined in detail including the criteria that triggered entering and exiting the collision avoidance rules. This test proved invaluable for refining the entry and exit criteria for stand on and give way rules. This image shows vehicles transiting to polygons in north and west zones.

Another method for robustness testing was to test the ability of a high contact density random environment of seven vessels that were seeking randomized points while complying with COLREGS. At a time of maximum complication, the tester suddenly instructed the autonomous marine vehicles to form a convoy while complying with COLREGS. This seven vehicle high contact density experiment was recorded and replayed in slow motion to ensure that all vehicles were complying with applicable rules even in a high contact density environment. One might relate this to a scenario similar to a high contact density of fishing vessels that are transiting between fishing points while not engaged in active fishing[2]. The advantage of this robustness testing technique was to not only see vessels remain compliant with the rules during a high contact density state, but also to allow testing of more dynamic scenarios with multiple rules and seven vessels simultaneously interacting.

The vessels are seen in random swarms as shown in Figure 3-12. Following an input command from the tester, the vehicles achieved a convoy by first exiting their current collision scenarios and then forming one behind the other according to resolution of rules and finally resolution of closest point of approach calculations. Further studies should consider using a collaborative decision scheme such as auction based collaboration or similar methods. The intermediate swarm transforming to a convoy while complying with COLREGS is shown in Figure 3-13. Finally the full convoy in the home plate pattern was achieved as shown in Figure 3-14.

3.5.3 In-Water Tests

Most research into collision avoidance of autonomous marine vehicles has focused on simulation or very limited in-water testing as described in Section 1.4. This study conducted a large amount of in-water testing to show that simulation results could be replicated with in-field results running the same behaviors. Of significance, multiple AMV types were run in the same field. Specifically the M100 and M200 Clearpath models described in Section 2.2.2 were both tested concurrently. A series of tests were conducted with two, three, four, and five autonomous marine vehicles in the same testing field at the same time. During the five vehicle on-water testing, the area used on the Charles River was expanded to allow for greater scope to capture effects of a large mission area. During testing, all vessels were running the collision avoidance algorithms for testing. Vehicles and objects not available within the MOOS-IvP

[2]In a scenario where these vessels were actively engaged in fishing operations, the tested rules of COLREGS within this study would no longer be applicable as a vessel engaged in fishing operations falls under a separate section of the Rules.

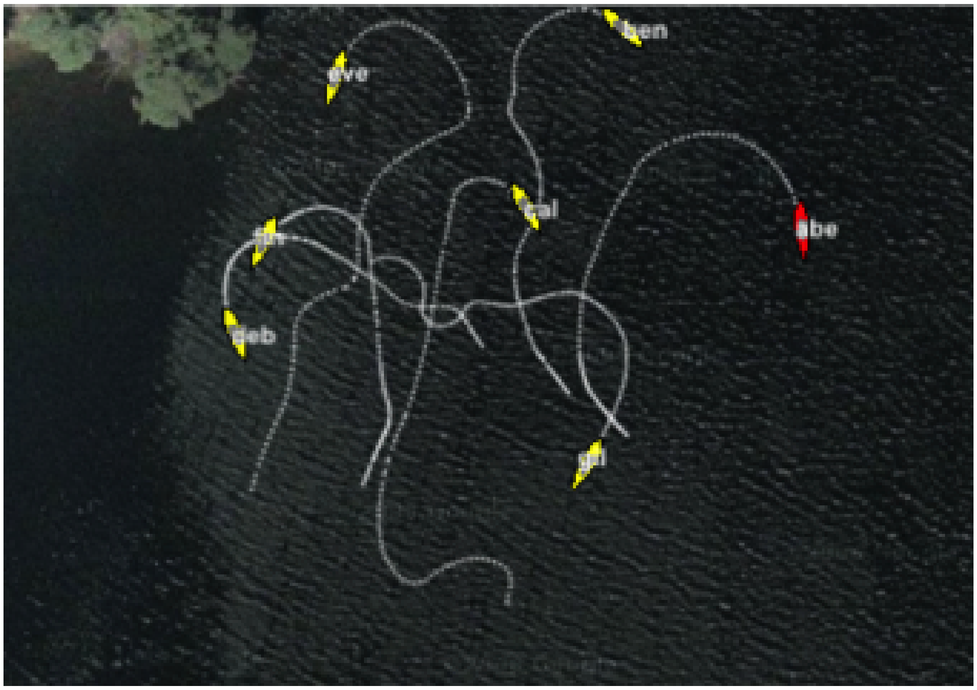

Figure 3-12: A swarm of seven autonomous marine vehicles was allowed to operate toward randomly generated points in a high contact density environment. The vehicles were maintaining collision avoidance in accordance with COLREGS and finally ordered to seek a convoy pattern to the south while maintaining collision avoidance.

environment were precluded from the testing space including sailboats, kayaks, and crew shells. An example of the tests run and viewed in reconstruction are shown in Figure 3-15.

A significant contribution of this study was to simultaneously test five autonomous marine vehicles using COLREGS-based collision avoidance in a real world environment simultaneously. The scope of real world testing was to demonstrate that actual vehicles in real world environments could successfully use the collision avoidance protocols to incorporate multi-vehicle dynamic encounters into the mission's multi-objective optimization scheme. Using the validation of these rules from the in-water tests, the high-encounter long duration simulations were then used for analysis using a design of experiments as described in detail throughout Chapter 4.

The in-water experiments using five vehicles concurrently were of particular importance as there are no known studies to have five autonomous vehicles actively avoiding each other using a COLREGS-based collision avoidance algorithm. Figures

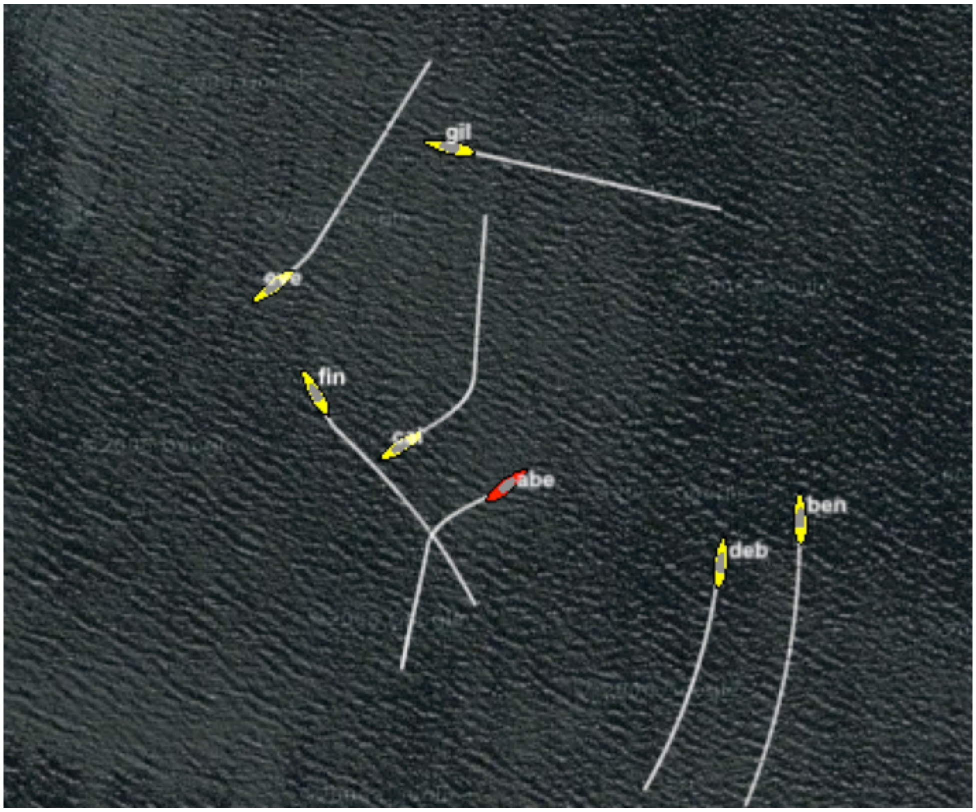

Figure 3-13: The seven vehicle swarm continued to resolve the pattern using collision avoidance with COLREGS.

3-16, 3-17, and 3-18 show examples of five vehicle collision avoidance being performed autonomously during testing at the MIT Autonomy Laboratory on the Charles River in Cambridge, MA.

The experiment in Figure 3-16 showed five vehicles interacting autonomously using COLREGS-based algorithms. Several scenarios resulted in all five vehicles concurrently interacting with each other for collision avoidance maneuvers such as the results shown in Figure 3-17. In these experiments, five vehicles were concurrently in head on and overtaking scenarios with each other.

The course was designed to allow for head on, overtaking, and crossing scenarios to result simultaneously while different speeds for each vehicle allowed for non-deterministic encounters at each approach as shown in Figure 3-18. The track history lines shown in white demonstrate non-recurring paths. This was all completed with real-world environmental conditions such as wind and current.

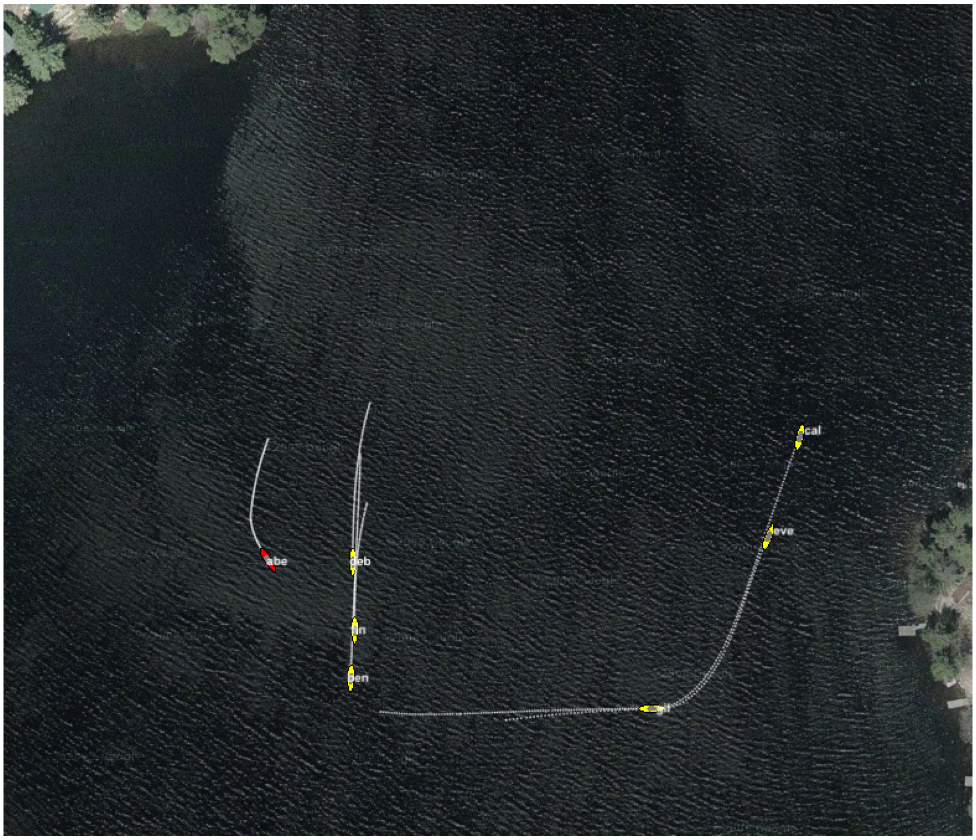

Figure 3-14: The seven vehicle swarm resolved the pattern using collision avoidance with COLREGS until the home plate pattern was achieved with all vehicles.

3.5.4 Uniformity of Field Tests and Simulation

Results in simulation were only considered to be meaningful and worthwhile if they could be shown to be relevant to real-world application. A powerful feature of testing using the MOOS-IvP architecture was that the exact same behaviors and settings experienced in simulation could be run on autonomous marine vehicles on the Charles River simply by loading the same code onto the vehicle. The only difference was that in simulation, the GPS coordinates and motor control signals were simulated. The output of in-water testing proved to validate the results of simulation allowing long-lasting Monte Carlo simulations to be run with high confidence that they represented real-world results.

The details of the testing are discussed in Chapter 4. The theory is described through an example before discussing the approach and results.

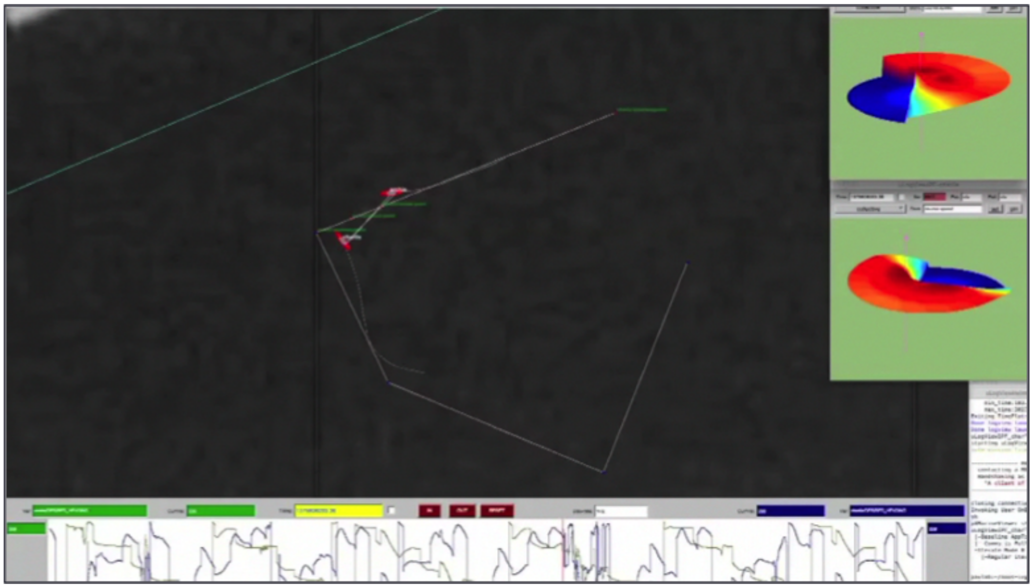

Figure 3-15: Tests were performed using in-water experimentation on the Charles River. Here a pair of vehicles approached a common waypoint and entered an active collision avoidance state to resolve their geometry. The two vehicles' collective objective functions are shown in the 3d polar plot representation at the top right of the display.

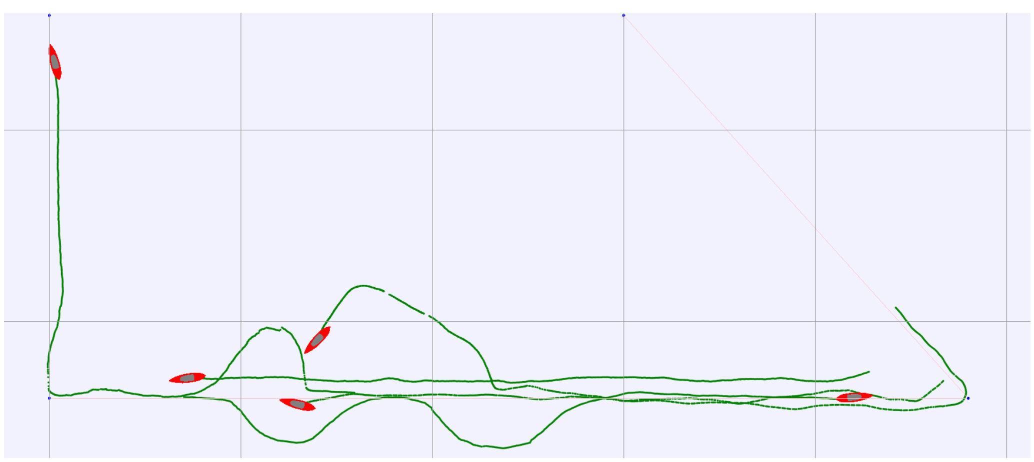

Figure 3-16: This experiment has five vehicles interacting autonomously using autonomous COLREGS algorithms on the Charles River. The five vehicles transited a polygon with interactions occurring non-deterministically. Each grid square was 50 meters by 50 meters.

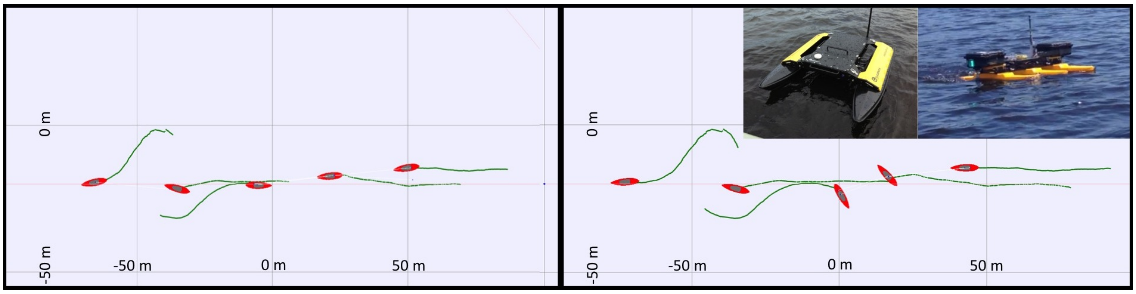

Figure 3-17: These experiments had five vehicles interacting autonomously using autonomous COLREGS algorithms. Here the five vehicles were concurrently in head on and overtaking scenarios with each other on the Charles River.

Figure 3-18: Here the five vehicles were on their polygon course using autonomous COLREGS algorithms. The course allowed for head on, overtaking, and crossing scenarios to result simultaneously while different speeds for each vehicle allowed for non-deterministic encounters at each approach. Note the track history lines in green that showed non-recurring action. This experimentation was completed on the Charles River with real-world environmental conditions such as wind and current using the M100 and M200 platforms discussed in Section 2.2.2.

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Chapter 4

Regression Testing and Analysis

4.1 Goals of Testing

Regression testing and analysis were performed to determine which collision avoidance parameters were most influential to reducing collisions while maximizing safety for autonomous marine vehicles. A design of experiments was conducted that allowed for variation of each parameter of interest. The results from the experiments were then analyzed to see how each parameter or combination of parameters affected safety and efficiency.

4.2 Design of Experiments

The purpose of conducting a design of experiments is to use known or suspected information about certain system parameters to run a series of experiments to determine their affects on system response and output [12, 21]. Once the parameters were identified and baseline values are established, the system could be tested with these parameters while varying their values in a predefined manner and observing the system response and output for resulting system behavioral changes.

To study the affects on the system with as few tests as possible, these parameters were assigned baseline values and nominally permuted to high and low values bounding the nominal values before being run in the experiments. These high and low parameter values were mapped to values of $+1$ and -1 respectively for the purpose of simplicity in tracking the experiment. By removing the scale and units of these parameters, the outcome is more readily seen for assembling and reading the table of experiments. An example of designed experimental testing of three variables is shown in Figure 4-1. For each of these example experiments, output of interest is measured allowing regression testing to be performed by examining the change of input to change of output for the entire design. If this three variable designed experiment had output of interest Y_1 and Y_2, then an example of the three principal parameters (X_1, X_2, X_3) and their combined effects $(X_1X_2, X_1X_3, X_2X_3, X_1X_2X_3)$ would be presented to the experimenter as shown in Figure 4-2. In this example, the pattern depicting a $+1$ or -1 for each main factor (X_1, X_2, X_3) is shown while their combined effects are simply their product. For example, if $X_1 = 1$ and $X_2 = -1$, then the combined effect of $X_1 * X_2$ would be evaluated as -1. This shows why the convention of $+1$ or -1 rather than scaled values with units is much easier for interpretation and experimentation.

Design

Run	X1	X2	X3
1	-1	-1	1
2	-1	1	1
3	1	1	-1
4	1	-1	1
5	-1	1	-1
6	1	1	1
7	1	-1	-1
8	-1	-1	-1

Figure 4-1: An example design of experiments for three variables using the JMP software package. Here a full 2^3 factorial experiment is presented as an example.

Once the experiment was conducted, the example outputs Y_1 and Y_2 would be analyzed to see how they changed based on permutations to the input variables. In linear regression, a combination of possible variables for a three parameter test would result in an equation similar to Equation 4.1 where β_i represents the coefficient corresponding to X_i. This equation represents the general result and analysis must then be performed on experimental output to determine which of the variables or

Pattern	X1	X2	X3	X1 X2	X1 X3	X2 X3	X1 X2 X3	Y1	Y2
−−−	-1	-1	-1	1	1	1	-1	Y11	Y21
−−+	-1	-1	1	1	-1	-1	1	Y12	Y22
−+−	-1	1	-1	-1	1	-1	1	Y13	Y23
−++	-1	1	1	-1	-1	1	-1	Y14	Y24
+−−	1	-1	-1	-1	-1	1	1	Y15	Y25
+−+	1	-1	1	-1	1	-1	-1	Y16	Y26
++−	1	1	-1	1	-1	-1	-1	Y17	Y27
+++	1	1	1	1	1	1	1	Y18	Y28

Figure 4-2: The design of experiments for a nominal three variable system is shown with two outputs. Outputs Y_{1i} and Y_{2j} would be measured for each of the 8 experiments conducted in this example.

combinations of variables were significant by conducting statistical analysis. Those variables that were not deemed to be statistically significant would then be removed entirely from the equation leaving only the significant factors in the final equation. An example final equation when only statistically significant variables are left might be similar to that of Equation 4.2.

$$Y = \beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + \beta_{12}X_1X_2 + \beta_{13}X_1X_3 + \beta_{23}X_2X_3 + \beta_{123}X_1X_2X_3 + \epsilon \quad (4.1)$$

$$Y = \beta_0 + X_1\beta_1 + X_2\beta_2 + X_3\beta_3 + \beta_{12}X_1X_2 + \beta_{123}X_1X_2X_3 + \epsilon \quad (4.2)$$

For a multivariate linear regression, the coefficients $\overrightarrow{\beta}$ are considered to appear linearly. The independent variables $\overrightarrow{X}$ can appear alone or as combinations such as $X_1 * X_2 * X_5$. An example linear regression equation from a similar design might have taken the form of Equations 4.3 and 4.4. Note that while the X_i variables do not appear linearly, all the coefficients β_i appear linearly. To determine which of the X_i variables appear and in what combinations, a regression test is performed to analyze significance of each variable. After performing an F-test for significance, each variable of interest can then be analyzed using a t-test. The result is that the variables of significance were identified and their respective coefficients $\overrightarrow{\beta}$ were determined.

$$Y_1 = \beta_{01} + X_2\beta_{21} + X_3\beta_{31} * X_4\beta_{41} + X_5\beta_{51} + \epsilon_1 \tag{4.3}$$

$$Y_2 = \beta_{02} + X_2\beta_{22} + X_3\beta_{32} * X_5\beta_{52} + \epsilon_2 \tag{4.4}$$

In this study, each of the five parameters of interest X_i was considered to be independent of each other. The resulting output was the dependent variables of safety and efficiency. By conducting this design of experiments, a determination of a model to describe how the independent variables affected each of the dependent variables were possible. While each X_i was determined a priori by design, the resulting Y_i output was found using long duration simulation which was validated by select in-water testing. These output values were then used to determine the unknown quantities β_i for each X_i in Equation 4.5.

$$\overrightarrow{Y} = f\{\overrightarrow{X}|\overrightarrow{\beta}\} \tag{4.5}$$

A two-variation method was used over a total of six variables[1] by conducting a 2^5 full factorial experiment for each of the two collision avoidance algorithms resulting in $2 * 2^5 = 64$ experiments. The specific parameters that were varied are discussed in Section 4.3 while the results are discussed later in this chapter. Final recommendations based on this analysis are given in Section 4.6. Additional experiments were performed to achieve a central composite design as described in Section 4.5.

4.3 Parameters Varied and Responses Measured

A design of experiments with regression analysis was conducted for each of the two algorithms (non-protocol generic and COLREGS) independently using the same variables to allow comparison of final results. These five variables were continuous positive numbers that were varied between high and low values. Two separate designs of experiments took place. The first design of experiments analyzed the affects of pa-

[1] Here "variables" loosely includes which algorithm was used. Strictly speaking, design of experiments requires only continuous variables for analysis, so this study has two separate designs each of five variables each.

rameters on the COLREGS-based algorithm while the second design of experiments focused on the generic non-protocol based algorithm. The following list describes the parameters that were varied for this experiment.

PWT_{inner} The range at which the active collision avoidance behavior had maximum priority weight in the interval programming objective function as defined by pwt_inner_dist.

PWT_{outer} The range at which the active collision avoidance behavior had zero priority weight in the interval programming objective function as defined by pwt_outer_dist.

CPA_{max} The resulting closest point of approach that carried maximum utility as defined by max_util_cpa_dist.

CPA_{min} The resulting closest point of approach that carried minimum utility as defined by min_util_cpa_dist.

$Speed_{relative}$ The speed of the slower autonomous vehicles. The faster vehicle was set at a fixed speed and the slower two vehicles assumed the variable value.

To allow for higher order modeling of the COLREGS-based experiment, a central composite design was used with a circumscribed composite. The star points for the design were calculated using the standard $F^{0.25} = 32^{0.25} = 2.3784$ relative to the nominal high and low values of $+1$ and -1 respectively. Here, F represented the number of full-factorial experiments. An example of a design of experiment in three dimensions is shown in Figure 4-3. A comparison of choosing star points using different types of designs is shown in Figure 4-4

Baseline values for each of the variables were identified using prior mission experience. Each of the parameters of interest X_i were tested at their high and low values for long duration simulations around a waypoint course. The waypoint course that was used allowed for crossing, overtaking, and head on geometries that were both canonical and non-canonical. All data was considered in the aggregate which allowed for an overall analysis that was not limited to any specific geometry. The repeated

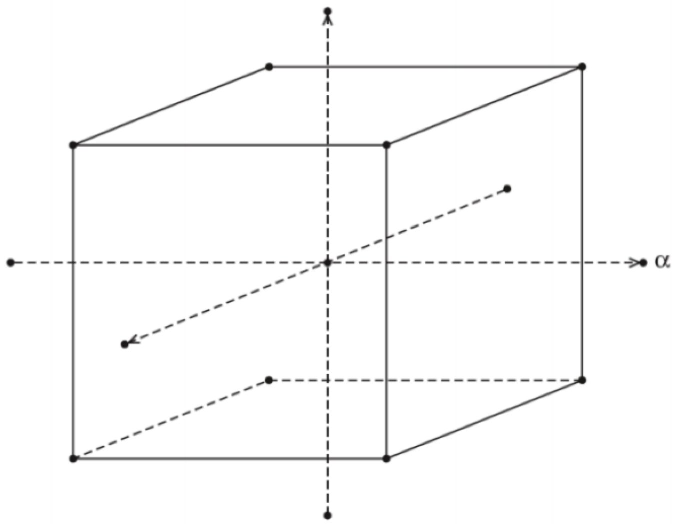


Figure 4-3: In three dimensions, a design of experiments can be represented using a cube where each face represents a different variable that was varied. A value of 1 corresponds to the high point, and a value of -1 corresponds to a low point. Notice that the corners of the cube represent the combination of high and low parameters. For values on a single axis, all variables are zero except one which assumes the value of the star point (α). The choice of α allows the designer to effectively choose the type of central composite design. Image courtesy of itl.nist.gov.

course over long temporal duration allowed for randomized approach characteristics to each waypoint relative to other contacts. The randomization in encounter range relative to other contacts enabled testing that was not simply a repeated situation but rather a dynamic approach as might be experienced in open ocean or real-mission scenarios. By inserting several vehicles onto the test course, an avoidance between vehicle A and vehicle B would likely result in track deviations to both vehicles causing course perturbations while approaching waypoints. This change in course allowed variations to relative encounter angle of a subsequent vehicle C that might also be approaching the same waypoint to that of A or B. The track geometry which had some nominal right angles in some locations would then see a de facto encounter angle much different than 90 degrees which helped to alleviate a stagnate canonical geometry experiment. The input parameters and their assigned values during regression are shown in Table 4.1.

To properly assess the impact of the varied parameters on both safety and efficiency, several responses were identified as being key to the study. The five response

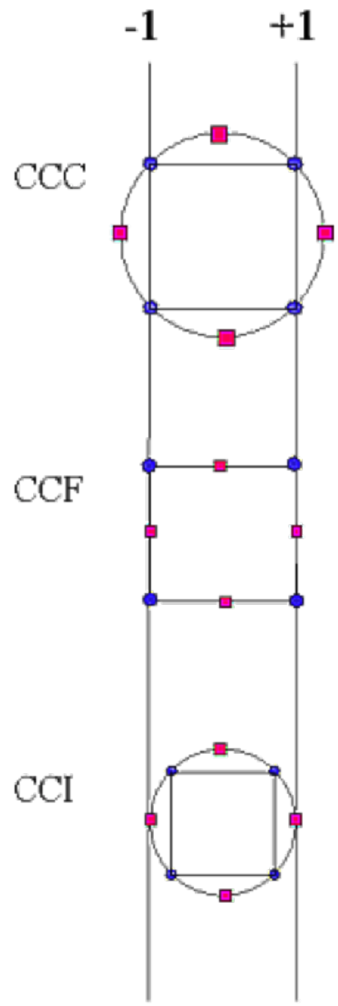


Figure 4-4: The design of experiments could be circumscribed, face-centered, or inscribed. Image courtesy of itl.nist.gov.

Mapped Values of Design of Experiment Parameter Values					
Mapped Values	**-1**	**1**	**-2.378**	**2.378**	**0**
Variables	**Low**	**High**	**Low Star**	**High Star**	**Zero**
pwt_outer_dist	15	30	11.3	33.7	22.5
pwt_inner_dist	5	10	3.8	11.2	7.5
min_util_cpa_dist	3.5	5	3.1	5.4	4.25
max_util_cpa_dist	10	25	6.3	28.7	17.5
speed	1	2	0.8	2.2	1.5

Table 4.1: Input parameters for regression testing assumed the values shown.

variables considered for the regression testing are listed in Table 4.2. The transiting leg efficiencies were measured to determine if a significant change would be noted based on a vessel starting its transiting leg significantly off track due to a collision avoidance maneuver immediately prior to the beginning waypoint being reached. Both mean and standard deviation efficiencies were of interest as a small change on mean would not necessarily imply an equal desirability. A mission designer might find much variation occurring with little change in average value to be equally as unattractive as a lower mean value based on particular mission objectives[2]. The Frequency of Collisions variable was determined by the ratio of collisions to the number of transited legs that included an active collision avoidance behavior as discussed in Section 2.6.1.

Response Variables for Regression Analysis	
Variable	**Name**
Y_1	Mean Transiting Efficiency
Y_2	Standard Deviation of Transiting Efficiency
Y_3	Mean Avoiding Efficiency
Y_4	Standard Deviation of Avoiding Efficiency
Y_5	Frequency of Collisions

Table 4.2: Five response variables were measured during testing to help determine the tradespace for efficiency and safety for collision avoidance.

4.4 Assumptions of Analysis

The model assumed in this study was linear for each of the outcomes

$\overrightarrow{Y} = \{Y_1, Y_2, Y_3, Y_4, Y_5\}$.

While a more accurate higher order model might be possible, the multivariate linear regression model proved to be sufficient for the purposes of identifying impact of each of the variables on safety and collision. All affects to the outcomes of interest were assumed to be results of the parameters varied with no significant impact of parameters outside the scope of the designed experiment. Long duration Monte Carlo experiments were conducted to ensure statistical significance of the number of interactions.

[2]For example, ocean bottom surveys desire little track deviation as their acoustic picture becomes quickly unusable if using a side scanning sonar.

4.5 Analysis Results

A regression analysis was performed for the COLREGS collision avoidance algorithm. The regression analysis for each of the three main response variables of interest (mean avoiding efficiency, standard deviation of avoiding efficiency, and safety as measured by collision fraction) are discussed in the following subsections. The remaining two response variables were primarily measured to establish a controlled baseline and ensure consistency between experimental environments.

4.5.1 COLREGS Algorithm

The COLREGS regression analysis consisted of examining a central composite design with circumscribed star points. This consisted of a 2^5 full factorial design with each of the five parameters taking a nominal value given in Table 4.1 and normalized to a value of ± 1. An experiment with all values set to the normalized zero was then performed with values assigned as shown in Table 4.1. All collision avoidance parameters were then set to their mapped zero value while one parameter at a time was changed to the star point of $\pm 2^{k/4} = \pm 2^{5/4} = \pm 2.3784$. This resulted in $2^5 + 1 + 2 \cdot 5 = 43$ experiments total for the COLREGS-based design.

The results were initially analyzed using MATLAB using the processes described in Appendix A. Each experiment was processed and examined. The aggregate of all experimental data was assimilated using another MATLAB script for graphical analysis using Excel. Determination of regression parameters was completed using both MATLAB and JMP[3].

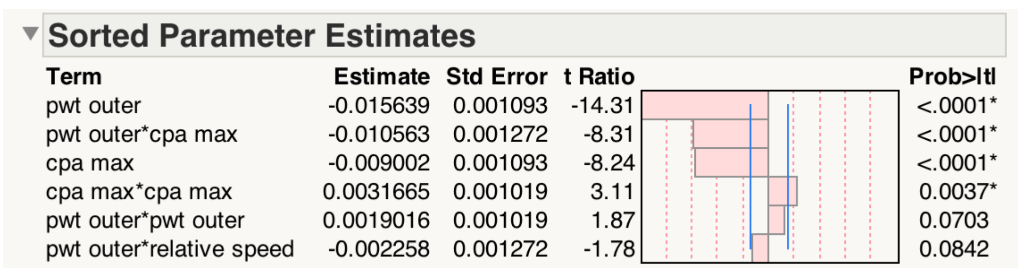
The COLREGS analysis was completed for the mean of avoiding leg efficiencies, the standard deviation of avoiding leg efficiencies, and the percent of collisions for all encounters.

[3] JMP is a statistical software package developed by SAS. JMP is often used in design of experiments (DOE), quality and productivity support (Six Sigma), and reliability modeling. Further information can be found at JMP's website (http://www.jmp.com/software/jmp/).

Mean Efficiency

The mean efficiency for all legs involving an active collision avoidance behavior was studied. The resulting regression analysis of the mean avoidance efficiency data showed a high degree of confidence with an R-squared value of $R^2 = 0.908$ with an adjusted R-squared value of $R^2_{adjusted} = 0.893$. The total root mean square error was $E_{rms} = 0.007$ with a mean response of 0.9315 for a total of 43 observations and five primary parameters considered. An F-ratio of 59.3107 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the main effect [4] of pwt_inner was entirely removed. Other effects were only left as compounding cross terms with the resulting two main effects of single variables being pwt_outer and cpa_max. The final parameter estimates are shown in Figure 4-5.


Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.015639	0.001093	-14.31	<.0001*
pwt outer*cpa max	-0.010563	0.001272	-8.31	<.0001*
cpa max	-0.009002	0.001093	-8.24	<.0001*
cpa max*cpa max	0.0031665	0.001019	3.11	0.0037*
pwt outer*pwt outer	0.0019016	0.001019	1.87	0.0703
pwt outer*relative speed	-0.002258	0.001272	-1.78	0.0842

Figure 4-5: The regression analysis for mean efficiency of avoiding legs using the COLREGS algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

The primary results of this analysis with respect only to the mean efficiency of legs involving collision avoidance were:

- the distance at which the AMV was allowed to start taking action for another contact was the most important single factor,

[4]Main effects are considered those variables that appear without compounding, that is X_i rather than $X_i \cdot X_j$. Main effects are generally considered to be more likely to be of significance than combined effects though in some cases such as this analysis, compounding effects were far more influential than other main effects.

- the second most important single factor was the desired distance at CPA otherwise known as *max_util_cpa_dist*,

- the geometric combination of the above two factors was a significant contributor with weight approximately equal to that of the desired CPA distance, and

- the only other significant factor of the five parameters studied was the square of the desired CPA distance.

The conclusions of the above list of relevant factors have several interesting points. Relative speed between the two vessels over the domain studied carried no significant impact on the mean efficiency for those legs involving a collision avoidance maneuver. The minimum acceptable CPA distance also carried no significant influence with respect to avoiding leg efficiencies. All the effects of importance described above carried negative correlation; that is, the higher the value (e.g., the larger the maximum CPA distance) the lower the efficiency.

If one were to reason about only maximizing efficiency for missions or waypoint legs involving a risk of collision where a maneuver may or may not be necessary, the analysis of these data indicated that maximizing efficiency would result from taking action as delayed as possible. This action would have of course disregarded the effects of safety but in a scenario where efficiency far outweighed safety, the resulting action would be to delay consideration of action as long as practicable. The interesting factor was that the distance at which action carried the most weight as given by pwt_inner was not statistically significant.

Further values of interest regarding the analysis for the mean of efficiency for COLREGS-based avoidance legs can be found in Appendix B.

Standard Deviation of Efficiency

The standard deviation of efficiency for all legs involving an active collision avoidance behavior was studied. The resulting regression analysis of the standard deviation of avoidance data showed a high degree of confidence with an R-squared value of $R^2 = 0.911$ with an adjusted R-squared value of $R^2_{adjusted} = 0.899$. The total root mean square error was $E_{rms} = 0.0068$ with a mean response of 0.0452 for a total of 43 observations and five primary parameters considered. An F-ratio of 75.5757 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the main effect of pwt_inner was entirely removed. Other effects were only left as cross terms with the resulting two main effects of single variables being pwt_outer and cpa_max. The final parameter estimates are shown in Figure 4-6.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	0.0137428	0.001028	13.37	<.0001*
cpa max	0.0103814	0.001028	10.10	<.0001*
pwt outer*cpa max	0.0114188	0.001196	9.55	<.0001*
cpa max*cpa max	-0.002299	0.000959	-2.40	0.0216*
pwt outer*pwt outer	-0.000721	0.000959	-0.75	0.4566

Figure 4-6: The regression analysis for standard deviation of efficiency of avoiding legs using the COLREGS algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

The primary results of this analysis with respect only to the standard deviation of efficiency for legs involving collision avoidance were:

- the distance at which the AMV was allowed to start taking action for another contact was the most important single factor,
- the second most important single factor was the desired distance at CPA otherwise known as *max_util_cpa_dist*,
- the geometric combination of the above two factors was a significant contributor with weight approximately equal to that of the desired CPA distance, and
- the only other significant factor of the five parameters studied was the square of the desired CPA distance.

This list was exactly the same as that of the mean of efficiency on avoiding legs with the exception of the signs for estimated values were negated. That is to say that as a parameter value increased, the resulting standard deviation of avoiding efficiency also increased. So in addition to the discussion above, as the range at which action was first considered was lowered, the standard deviation of efficiency was also reduced. The result of combining the above discussion with these findings was that the lowering of the first range at which a collision avoidance maneuver was considered not only resulted in better efficiency, but it also resulted in a slightly more predicable efficiency. Again, the caution with this statement was that the analysis fully disregards the resulting safety of taking late action and not considering action until a closer range to a contact.

Further values of interest regarding the analysis for the standard deviation of efficiency for COLREGS-based avoidance legs can be found in Appendix B.

Collision Frequency

Collision frequency (or percentage) was regressed using several transformations in an attempt to obtain the highest correlation value. The transformations considered included the raw data (no transformation), a $\log_{10}(CF)$ transformation and a natural logarithmic transformation $\ln(CF)$, a square transformation CF^2, an exponential transformation e^{CF}, a square root transformation $\sqrt{CF}$, a cubic root transformation $\sqrt[3]{CF}$, and a quartic root transformation $\sqrt[4]{CF}$, where CF denotes the untransformed collision fraction.

To determine the strength of the regression, the adjusted R-squared values were considered rather than just the R-squared values to account for the number of data present compared to the number of variables being regressed. The transformation with the highest adjusted R-squared value was the quartic root of collision fraction with an adjusted R-squared value approximately equal to 0.687.

The R-squared values for other transformations ranged from 0.392 to 0.682 and correlated to the transformations as follows:

- no transformation $CF \approx 0.56$,
- $\log_{10}(CF) = \ln(CF) \approx 0.628$ transformation,

- a square transformation $CF^2 \approx 0.392$,
- $e^{CF} \approx 0.536$,
- a square root transformation $\sqrt{CF} \approx 0.657$,
- a cubic root $\sqrt[3]{CF} \approx 0.682$ transformation, and
- a quartic root $\sqrt[4]{CF} \approx 0.687$ transformation where CF denotes the original collision fraction.

The collision fraction for all legs involving an active collision avoidance behavior was studied using the quartic root transformation of collision fraction as identified above. The resulting regression analysis of the collision fraction transformed data showed a moderately high degree of confidence with an R-squared value of $R^2 = 0.724$ with an adjusted R-squared value of $R^2_{adjusted} = 0.687$. The total root mean square error was $E_{rms} = 0.116$ with a mean response of 0.373 for a total of 43 observations and five primary parameters considered. An F-ratio of 19.4434 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the resulting parameters with statistical significance included the range at which action was first considered (pwt_outer), the product of PWT_{outer} and CPA_{min}, and the product of PWT_{inner} and CPA_{max} as shown in Figure 4-7.

The collision fraction metric for safety showed interesting results for statistical significance in that two opposite results were acting:

- the product of distance that action was first considered and the minimum desired CPA range reduced collision frequency (negative correlation resulted),
- the product of the distance with highest priority weight and the maximum desired CPA range further reduced collision frequency (negative correlation resulted).

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.156195	0.018025	-8.67	<.0001*
pwt outer*cpa min	-0.06913	0.020971	-3.30	0.0022*
pwt inner*cpa max	-0.049685	0.020971	-2.37	0.0232*
pwt outer*pwt outer	0.028936	0.016393	1.77	0.0858
pwt inner*cpa min	-0.033361	0.020971	-1.59	0.1202

Figure 4-7: The regression analysis for collision percentage of avoiding legs using the COLREGS algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

The only main effect significant to the regression was the range at which a maneuver was first considered PWT_{outer}. This value carried significant weight in the reduction of collisions with an estimated coefficient value of -0.156 (negative correlation) compared to the next closest contributing parameter with an estimated coefficient value of -0.691 (negative correlation). The take away from this is that the most important factor to consider when desiring a lower risk of collision as measured by the long term statistical frequency of violating a safety stand off range was to consider action as early as practicable. This early action indicator to avoid collisions was in direct conflict with the above findings to maximize efficiency by delaying consideration of the range at which action was first considered thus scientifically verifying what many experienced captains would submit by intuition: there exists a directly competing objective between mission efficiency and overall safety when considering the aggregate of all rules within this study.

Further values of interest regarding the analysis for the collision frequency of COLREGS-based avoidance legs can be found in Appendix B.

4.5.2 Non-Protocol Algorithm

The non-protocol based algorithm was also analyzed for mean efficiency, standard deviation of efficiency, and collision percentage. A 2^5 full factorial design was used without the additional expense for a central composite design. The intention of this design was to examine if the same collision avoidance parameters that were important to affecting the response variables of the COLREGS-based algorithm were also important to the non-protocol based algorithm.

Mean Efficiency

The mean efficiency for all legs involving an active collision avoidance behavior using the non-protocol based algorithm was studied. The resulting regression analysis of the mean avoidance efficiency data showed a high degree of confidence with an R-squared value of $R^2 = 0.947$ with an adjusted R-squared value of $R^2_{adjusted} = 0.909$. The total root mean square error was $E_{rms} = 0.006$ with a mean response of 0.936 for a total of 32 observations and five primary parameters considered. An F-ratio of 24.9518 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the final parameter estimates were found and are shown in Figure 4-8.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>ltl
pwt outer*cpa max	-0.011139	0.001055	-10.56	<.0001*
cpa max	-0.00853	0.001055	-8.08	<.0001*
pwt outer	-0.006832	0.001055	-6.48	<.0001*
pwt outer*cpa min	0.0047166	0.001055	4.47	0.0003*
cpa min*cpa max	0.0042397	0.001055	4.02	0.0008*
cpa min	0.0037541	0.001055	3.56	0.0022*
pwt inner	-0.003717	0.001055	-3.52	0.0024*
pwt outer*cpa max*relative speed	-0.003537	0.001055	-3.35	0.0036*
cpa max*relative speed	-0.00309	0.001055	-2.93	0.0090*
pwt outer*pwt inner*cpa min*cpa max	0.0030441	0.001055	2.88	0.0099*
pwt inner*cpa min	0.0027147	0.001055	2.57	0.0192*
pwt inner*relative speed	0.0026347	0.001055	2.50	0.0224*
pwt outer*cpa min*cpa max	0.0019622	0.001055	1.86	0.0794

Figure 4-8: The regression analysis for mean efficiency of avoiding legs using the Non-Protocol Generic Algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

The primary results of this analysis with respect only to the mean efficiency of legs involving non-protocol based collision avoidance were:

- many main effects and compounding effects proved statistically significant,

- the only main effect to not appear without compounding was relative speed (all other main effects were significant without compounding), and
- much more compounding was significant in the non-protocol based regression indicating that the non-protocol based approach requires much more thought if trying to maintain an efficient operating environment which was consistent with less predictable maneuvers.

Further values of interest regarding the analysis for the mean of efficiency for non-protocol based avoidance legs can be found in Appendix B.

Standard Deviation of Efficiency

The standard deviation of avoiding efficiency for all legs involving an active collision avoidance behavior using the non-protocol based algorithm was studied. The resulting regression analysis of the avoiding standard deviation of avoiding efficiency data showed a high degree of confidence with an R-squared value of $R^2 = 0.900$ with an adjusted R-squared value of $R^2_{adjusted} = 0.865$. The total root mean square error was $E_{rms} = 0.008$ with a mean response of 0.0463 for a total of 32 observations and five primary parameters considered. An F-ratio of 25.8981 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the final parameter estimates were found and are shown in Figure 4-9.

The primary results of this analysis with respect only to the standard deviation of efficiency for legs involving non-protocol based collision avoidance were:

- the most influential parameter was the product of PWT_{outer} and CPA_{max},
- CPA desired distance was the most important main effect,
- three main effects including both CPA_{max},PWT_{outer}, and PWT_{inner} were statistically significant, and
- relative speed was important but only as a compounding effect.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer*cpa max	0.0126899	0.001464	8.67	<.0001*
cpa max	0.0113708	0.001464	7.76	<.0001*
pwt outer	0.009976	0.001464	6.81	<.0001*
pwt inner	0.0037424	0.001464	2.56	0.0177*
cpa max*relative speed	0.0034823	0.001464	2.38	0.0261*
pwt inner*relative speed	-0.003332	0.001464	-2.27	0.0325*
pwt outer*pwt inner*cpa min*cpa max	-0.003145	0.001464	-2.15	0.0425*
pwt outer*cpa min	-0.002713	0.001464	-1.85	0.0768

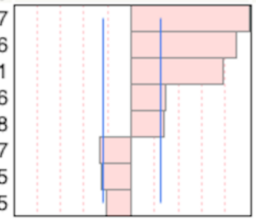


Figure 4-9: The regression analysis for standard deviation of avoiding legs using the Non-Protocol Generic Algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

Further values of interest regarding the analysis for the standard deviation of efficiency for non-protocol based avoidance legs can be found in Appendix B.

Collision Frequency

The collision frequency for all legs involving an active collision avoidance behavior using the non-protocol based algorithm was studied. The resulting regression analysis of the mean avoidance efficiency data showed a high degree of confidence with an R-squared value of $R^2 = 0.972$ with an adjusted R-squared value of $R^2_{adjusted} = 0.925$. The total root mean square error was $E_{rms} = 0.029$ with a mean response of 0.206 for a total of 32 observations and five primary parameters considered. An F-ratio of 20.68 was found with a resulting $Prob > F$ of < 0.0001.

After several iterations to best approximate the parameters of significance to include the factors as described in Table 4.1, the final parameter estimates were found and are shown in Figure 4-10.

The primary results of this analysis with respect only to the collision frequency for legs involving non-protocol based collision avoidance were:

- PWT_{outer} was the most influential parameter and had negative correlation consistent with the COLREGS-based algorithm,
- relative speed entered the non-protocol based algorithm's estimation space as a compounding variable but was completely absent from the COLREGS-based algorithm,

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.06741	0.005205	-12.95	<.0001*
pwt inner*cpa max	-0.03176	0.005205	-6.10	<.0001*
cpa max*relative speed	0.0303135	0.005205	5.82	<.0001*
pwt outer*pwt inner*cpa min	0.022714	0.005205	4.36	0.0009*
pwt outer*cpa min	-0.021892	0.005205	-4.21	0.0012*
pwt outer*pwt inner*cpa max	0.0212119	0.005205	4.08	0.0015*
pwt inner	-0.020256	0.005205	-3.89	0.0021*
pwt outer*cpa max*relative speed	0.0201902	0.005205	3.88	0.0022*
pwt inner*relative speed	-0.020047	0.005205	-3.85	0.0023*
cpa min*cpa max	-0.018799	0.005205	-3.61	0.0036*
pwt outer*pwt inner*cpa min*cpa max	-0.017057	0.005205	-3.28	0.0066*
pwt outer*pwt inner*relative speed	0.0146607	0.005205	2.82	0.0156*
pwt outer*pwt inner	0.0145817	0.005205	2.80	0.0160*
pwt outer*cpa max	0.0138854	0.005205	2.67	0.0205*
cpa min	-0.013166	0.005205	-2.53	0.0264*
pwt outer*pwt inner*cpa min*relative speed	-0.012371	0.005205	-2.38	0.0350*
cpa max	0.0114931	0.005205	2.21	0.0474*
pwt inner*cpa min	-0.011188	0.005205	-2.15	0.0527
pwt outer*cpa min*cpa max	0.0109198	0.005205	2.10	0.0578
cpa min*relative speed	0.0101337	0.005205	1.95	0.0753

Figure 4-10: The regression analysis for collision frequency of avoiding legs using the Non-Protocol Generic Algorithm resulted in the summary of significant parameters as shown. Statistically significant parameters included those with a probability value less than 0.05 which also appear with an asterisk on the right-most column.

- many more factors of both main effect and compounding effect were statistically significant in the CPA analysis as compared to the COLREGS analysis for collision frequency,
- both CPA ranges and both instantaneous ranges (PWTs) appeared as main effects unlike only one main effect in COLREGS, and
- both the CPA and COLREGS estimates showed a single dominating factor of PWT_{outer} with other effects having a much less influential weight.

Further values of interest regarding the analysis for the collision frequency of non-protocol based avoidance legs can be found in Appendix B.

4.5.3 Comparison of the Algorithms

In addition to the details presented already in Section 4.5, the charts in Appendix C give graphical insight to the differences between non-protocol based and COLREGS-based approaches to collision avoidance. Descriptions of the organization of results data are shown below followed by efficiency and safety results while the relevant charts can be found in Appendix C.

Long-Duration Mean Efficiency for Avoiding Legs The mean of efficiency for each experiment was plotted to show the expected change in efficiency for a given set of parameters. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms.

Total Avoiding Legs The total avoiding legs chart shows the number of interactions for each experiment. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. Here, the total simulations per experiment were shown where on average 10^4 experiments were performed for any given set of parameters. The mean value of avoiding legs per configuration was $9857 \approx 10^4$.

Avoiding Legs Standard Deviation The standard deviation of efficiency for each experiment was plotted to show the variation in efficiency predictability for a given set of parameters. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. From the chart, it is clear that the CPA and COLREGS algorithms have similar standard deviations for the same set of collision avoidance parameters.

Efficiency Factor The efficiency factor showed the ratio of non-protocol based to COLREGS-based algorithms. An efficiency factor of one represented both algorithms yielding the same level of efficiency where efficiency was the ratio of linear distance between waypoints to actual odometer distance traveled between waypoints as defined in Section 2.4.2. From the chart, it was clear that many experiments were almost of the same efficiency value while several combinations were indeed more efficient by using the COLREGS-based algorithm.

Safety Improvement Factor The safety improvement factor graphically displayed the ratio of collision fraction for the non-protocol based and COLREGS-based algorithms. A blue bar indicated that the non-protocol based algorithm resulted in a higher collision fraction than the COLREGS-based algorithm. A red bar indicated that the COLREGS-based algorithm exceeded the non-protocol based algorithm in collision frequency. Note that almost all cases were in favor of using the COLREGS-based algorithm with respect to safety. The three experiments that have a number rather than a histogram represent the experimental configurations resulting in zero collision ring violations for the COLREGS-based algorithm out of approximately 10^4 interactions. These values with percentage signs ($0.6\%, 0.3\%$, and 0.2%) represent the three values of collision fraction in the non-protocol based algorithm for their respective zero collision COLREGS settings. This chart was quite influential as it clearly shows that safety improvements as measured by reduction in collision frequency were as high as 272 times. Most safety reductions were approximately 4-25 fold with an average safety improvement factor of 18.39. Given the efficiency improvements gained as shown on the Efficiency Factor chart, these safety improvements were very powerful evidence for choosing a COLREGS-based approach for collision avoidance even in environments with complete exclusion of manned vehicles. Data showing the comparative data of the safety improvement factor between the two algorithms is shown in Table 4.3.

Collision Percentages for Avoiding Legs The collision percentages chart showed the ratio of encounters involving collisions to all encounters between vehicles. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. The ratio of blue and red charts was shown as the previously described Safety Improvement Factor. Of note, several combinations resulting in high collision frequency were due to edge case experiments in simulation where CPA range was at or near the collision range ring. These were not desired settings but rather showed the importance of choosing a CPA with considerable safety margin as to avoid the delays associated with navigation of a vessel which might result in an unintended collision.

Total Collisions for Avoiding Legs The total collisions chart showed the number of collisions for each experiment. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. To be meaningful, this raw data was normalized using the total avoiding legs to determine the collision percentage. The collision percentage was then compared between CPA and COLREGS algorithms to creat the safety improvement factor.

Long-Duration Mean Efficiency for Transiting Legs The mean of efficiency for each experiment was plotted to show the expected change in efficiency for a given set of parameters. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. These were legs that did not involve collision avoidance being active to show that efficiencies were quite similar between experimental parameters. The variation of mean efficiency can be accounted to situations where the vehicle did not start exactly at the waypoint due to being off track as a result of a collision avoidance maneuver on the previous leg.

Total Transiting Legs The total transiting legs chart shows the number of interactions for each experiment. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. Here, the total simulations per experiment were shown where on average approximately $9857 \approx 10^4$ experiments were performed for any given set of parameters and an average of 6877 transiting legs per experiment were used to verify the control outputs did not shift between experiments.

Transiting Legs Standard Deviation The standard deviation of efficiency for each experiment was plotted to show the variation in efficiency predictability for a given set of parameters. The blue graphs represent non-protocol based algorithm experiments while red represents COLREGS-based algorithms. From the chart, it is clear that the CPA and COLREGS algorithms have similar standard deviations for the same set of collision avoidance parameters in most cases, though the cases with a higher split indicate the changes of being off track as a result of a collision avoidance maneuver.

Of particular interest in the charts was the overall comparisons of mean avoiding efficiency and safety improvement factor. The mean of means was computed for avoiding efficiency. The non-protocol based algorithm resulted in an overall global efficiency of 0.9351 while the COLREGS-based efficiency had an overall global efficiency of 0.9315. The ratio of the two results was 99.618% implying a 0.4% reduction in efficiency on a global average basis. The efficiency could be considered to be relatively unchanged and quite attractive when considering the safety improvement factor discussed below.

Safety improvement factor results are shown in Table 4.3. Of the 32 experiments conducted with both algorithms, COLREGS proved safer in 21 cases with an average safety improvement factor of 18.39. This means that in the 21 of 32 cases where COLREGS was safer than the non-protocol based algorithm, an average of over 18 times reduction in collisions was seen on an experiment-to-experiment comparison. For the 14 experiments where the non-protocol based algorithm proved ultimately more safe, the average of these safety improvements was only 0.91. That is, the average improvement was less than a factor of one compared to an 18 fold increase for the CPA-dominated cases. Those cases where CPA was "safer" mostly correlated to the low setting for PWT_{inner} signifying that taking action once in extremis and a collision was imminent slightly favored an unconstrained non-protocol based evasion. The very small gain in safety coupled with the insightful design choice of choosing a pre-collision value for requiring collision avoidance action should shift the safety improvement almost wholly toward the COLREGS-based approach.

When considering the actual collision percentages rather than the safety improvement factor, the data showed a distinct improvement in safety for the COLREGS algorithm when transitioning from the left half to the right half of the graph. This corresponded a shift in a single variable: on the left half *pwt_outer_dist* was low and on the right half *pwt_outer_dist* was high. This result shows that the COLREGS safety was much better when action could be taken early. A possible explanation for this could be that a rule such as stand on might be currently precluding a rule 17(a)(ii) evasive maneuver to starboard prior to when action would be appropriate. Further refinement of the COLREGS-based algorithm could study whether any changes to the range at which rule 17(a)(ii) evasive action to starboard could be taken by a stand on vessel and whether this significantly reduces the number of collisions in the left half of this graph.

Put into perspective, one can immediately see that the nearly identical efficiencies result in drastic safety improvements for approximately two-thirds of the experimental conditions while the remaining experiments have a relatively unchanged safety factor. The results proved clear: using a COLREGS-based algorithm rather than a non-protocol based collision avoidance technique offers significant safety gains overall with little to no loss of efficiency especially for those cases where action was taken early[5].

4.6 Recommendations for Solution Improvements

If considering a similar design of experiments to study the effects of collision avoidance parameters on efficiency and safety, one might expand the scope of the study to vessels considerably larger than those available to on-water tests for this work. If larger vessels with a more open domain could be studied, another study might conclude that these results scale or might find that the size of the vessel and its resulting ability to maneuver might significantly affect the outcomes of such prediction parameters. Further consideration should be given to expanding the domain of the normalized parameters to include a larger scope of values for CPA and decision ranges as well as relative speed. An entirely new area of research that would require development prior to study would be introduction of approximate vehicle dynamics into the decision space of an autonomous vehicle. Allowing more accurate prediction of future vehicle position based on maneuvering characteristics would presumably allow for greater safety.

[5]Taking early action corresponds to *pwt_outer_dist* being at a relatively high value.

Table 4.3: Comparison of Safety Improvement Factors. For the three values marked Inf, the COLREGS algorithm had zero collisions for the parameter combination while the generic collision avoidance algorithm resulted in a finite number of collisions. This would result in a ratio of infinity. In the corresponding Safety Improvement Factor chart in Appendix C, these values are marked with the percentage of times that the generic algorithm resulted in a collision.

Experiment Number	COLREGS Safer	CPA Safer
1	6.55	–
2	4.12	–
3	–	1.64
4	24.12	–
5	–	1.36
6	–	2.93
7	–	1.77
8	–	1.69
9	–	1.15
10	–	4.48
11	–	1.56
12	5.71	–
13	–	1.59
14	–	4.63
15	–	6.42
16	3.79	–
17	6.17	–
18	39.46	–
19	9.56	–
20	4.31	–
21	25.82	–
22	5.93	–
23	Inf	–
24	154.73	–
25	3.03	–
26	Inf	–
27	6.42	–
28	6.96	–
29	3.72	–
30	6.04	–
31	Inf	–
32	272.05	–
sum	588.49	29.21
average	18.39	0.91
# experiments with superior safety	21.00	14.00

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Chapter 5

Recommended Autonomous COLREGS Certification Standard for Autonomous Marine Vehicles

5.1 Future of COLREGS on Autonomous Marine Vehicles

With COLREGS being used on vessels throughout the world, it would be highly burdensome to change to a different rule set for the integration of autonomous marine vehicles into the manned domain. Rather, incorporating the COLREGS rule base into the operations of autonomous marine vehicles makes the most sense. Much research has been conducted for visual and radar systems integration to autonomous decision making. COLREGS and the many protocols for interactions of vessels on the high seas have evolved for centuries. The incorporation of autonomous marine vehicles is a unique case that offers a chance for this robust protocol and rule set to further incorporate the changing of our culture and technology. Much like the claim of Judge William H. Brawley used to open Henderson's discussion of the legality of UUVs [14], COLREGS can be seen as having underlying principles which will indeed adapt themselves to the new developments including autonomous unmanned vessels.

As Henderson correctly claimed, Judge Brawley's observation perhaps showed more foresight than one might have assumed at the time.

> [S]o far reaching are the principles which underlie the jurisdiction of the courts of admiralty that they adapt themselves to all the new kinds of property and new sets of operatives and new conditions which are brought into existence in the progress of the world. [2]
>
> Judge William H. Brawley (1896)

5.2 Proposed Requirements for Identification as AMV

This study recommends that autonomous marine vehicles should comply with all current provisions of the COLREGS with some additional requirements for identification as an autonomous vessel. The additional identification requirements are outlined in the following sections.

5.2.1 Lights

All running and special signal lights required by COLREGS should be incorporated into autonomous marine vehicles on the open ocean. In addition to these lights, a signal unique to the autonomous community should be used to warn vessels in the vicinity that they are an autonomous unmanned vessel and currently unable to respond in ways that might be achievable by a manned vessel such as VHF bridge-to-bridge radio.

A unique identification light already has precedent in COLREGS for submarines which currently display an amber light which flashes three short signals followed by a three second pause (Morse code for the letter "s").

> "Submarines may display, as a distinctive means of identification, an intermittent flashing amber beacon with a sequence of operation of one flash per second for three (3) seconds followed by a three (3) second off-period (32 CFR 707.7). [1]"

Similarly, this study recommends that autonomous marine vehicles be fitted with a distinctive identifying flashing amber beacon with a sequence of operation of one flash per second for two seconds followed by one flash for three seconds followed by a three second off-period ($\cdot\cdot-$). This short-short-long combination is Morse code for the letter "U" signifying an unmanned vessel with a standard three-time unit long intermittent period.

5.2.2 Sounds

All normal sounds and audible signals required by COLREGS Rules 32 - 37 should be incorporated and followed by autonomous vessels. For those situations where the autonomous vessel finds itself unable to operate autonomously and becomes effectively "not under command" this study recommends that the AMV should take action per Rule 35(c) and "sound at intervals of not more than 2 minutes three blasts in succession, namely one prolonged followed by two short blasts. [1]"

This sounding behavior would also be appropriate for situations where the autonomous marine vehicle was unable to detect other vessels such as degradation of detection or processing equipment; however, the sound signals should not be used more generally for the sole purpose of drawing attention to an autonomous marine vehicle if otherwise operating within the Rules.

5.3 Necessary Technological Advances

Several technological advances are required before autonomous vessels can seamlessly enter the manned vessel world. Three major areas are discussed below including advances in above water acoustic detection and reasoning, advances in AIS communication, and advances in VHF bridge-to-bridge radio communications between manned and unmanned vessels. Researchers are encouraged to develop solutions to these problems to advance the capabilities of autonomous vessels who are operating in manned environments.

5.3.1 Above Water Acoustics

An area of much needed improvement is non-visual sensing that would otherwise be available to a human without technology. The primary means of this sensing is listening to the above-water environment [13]. An area with little to no known scientific research is automatic detection of horns, bells, gongs, and other audible signals above the waterline. This detection and classification capability becomes essential in situations of "reduced visibility" where a visual detection apparatus or radar detection might be significantly degraded.

Most acoustic systems used to detect surface vehicles are ground-fixed passive underwater sensors [30]. Research at the Army Research Laboratory has used acoustic arrays to detect and localize sniper fire and other impulsive noise events [35]. Young et al integrate these acoustic sensors on ground-based robots to direct other sensors such as cameras. Research to date has not introduced a similar concept to the marine environment to look for prolonged tones of known frequencies that might correspond to a ship's whistle or a fog horn. Further studies by Young et al [36] have introduced an acoustic payload consisting of an eight-channel microphone array small enough to be carried on ground-based robotic platforms which would serve as inspiration for a marine-focused above-water sensing array to detect ship's signals.

A means of an acoustic vessel to detect, classify, and correctly maneuver based on a received audio signal such as a horn, bell, or gong is a fundamentally unsolved but important aspect to realizing autonomous compliance of COLREGS[1]. An autonomous vessel must also be able to appropriately respond to these perceived acoustic signals

[1]Rules 32-37 of the Rules define the "Sound and Light Signals" that are required aboard vessels. This section of COLREGS defines the appropriate devices and their signals as well as identifies when each signal is appropriate or required.

with its own devices such as the ship's whistle.

The following advances are recommended for above-water acoustic sensing and signaling for contact management:

- integrate an above-water onboard acoustic array to detect other acoustic signals (horns, gongs, bells, etc.) of vessels and navigation markers
- develop an algorithm to use this acoustic data to further populate the contact picture and act accordingly
- develop an algorithm to respond in accordance with the Rules to other vessels using audible sounds, visual cues, and radio broadcasts as appropriate.

5.3.2 AIS Advancements

For situations where an immediate voice conversation might not be necessary, communications via the Automated Information System (AIS) protocol is standard practice between manned vessels. Designing a means for manned and autonomous systems to communicate and resolve potential risks of collisions via AIS would further reduce the necessity for voice communications.

Advances using the Automated Information System (AIS) could include the following:

- develop algorithms for AMV-AMV communication for vehicles not previously known to each other
- create a system for communication between manned vehicles and AMVs not previously known to each other
- develop an algorithm for acceptance of intentions from other vehicles via digital communications
- develop an algorithm for acceptance of queries from other vehicles via digital communications

- establish a method for response to queries to other vehicles via digital communications

Authors have identified the need to integrate AIS information with evolving platforms and uses over the years [32]. This includes encouraging technology that complies with the intention of the International Maritime Organization's primary AIS standards of a ship-to-ship mode for collision avoidance, allowing littoral States access to information about ships and their cargo[2], and allowing a more general traffic management scheme [15].

Reporting intervals, standards, and protocols have been established for digital information exchange between manned vessels using AIS [16]. Within territorial waters, individual countries place additional broadcasting requirements on vessels using AIS [10]. By integrating AIS into the autonomous vessel's contact picture, detection of other vessels not gained in primary sensors such as radar becomes possible by use of the AIS static messages. Of increased interest but not yet developed is the ability to communicate between an autonomous and manned vessel using dynamic text-based messaging for query and response as well as voice-based communication using the Digital Selective Calling service over the Global Maritime Distress and Safety System protocol. The protocol currently exists for manned operations but has not been exploited to allow for direct human communication with an autonomous vessel.

5.3.3 VHF Advancements

In many cases where two manned vessels are at risk of collision, they resolve the situation via a short verbal arrangement using bridge-to-bridge radio. When one or both of these vehicles is autonomous, an adaptive algorithm must be established to allow an AMV the ability to understand, communicate, and negotiate with the manned vessel to resolve the risk of collision.

Advances in Voice Communications (VHF Bridge-to-Bridge Radio) could include

[2]AIS technology is increasingly used to provide for maritime domain awareness with protective organizations such as the US Coast Guard and other similar maritime regulatory agencies throughout the world.

the following:

- create a method of communication of intentions from an AMV to other vessels via VHF maritime radio using simulated human voice

- develop algorithms to receive and interpret voice communications from manned vehicles using VHF maritime radio

- develop an algorithm to integrate information received via voice communications to further populate the contact picture and maneuver appropriately

- develop an algorithm to receive, understand, and respond to queries of manned vessels using only VHF radio (e.g., no AIS available)

Current research has not crossed into the application of speech recognition software onboard autonomous marine vessels. Many speech recognition programs and applications have been studied, though the application to an autonomous vessel interpreting a manned vessel's VHF or GMDSS-DSC radio communication has not been attempted. Recent literature does however investigate oral communications using the English language[3] as it applies to maritime communications both onboard and between vessels [23]. Investigations have looked at how oral communication has led to mistakes between manned vessels including grammar, lexicon, word order, and perceived spelling [22] as well as steps to improve oral communication between vessels on the high seas. Improvements include training to ensure a radio channel is clear of traffic, avoiding superfluous or redundant content, addressing another vessel indistinguishably, and being explicit with the message contents to ensure no misunderstandings [23], all of which should be applied to autonomous vessel voice communications. Other research looks at the ability of an autonomous vessel to radio for help using non-voice communications to its manned operations center if unable to act appropriately in an autonomous mode [29] but has not considered expanding this to communicating with other vessels in the vicinity.

[3]The English language is the official language for maritime radio communications as adopted by the IMO.

For both AIS and VHF, a means of incorporating data received from other vessels into ownship's contact picture and allowing for correct and timely processing of relevant rules and regulations must be established. Further, results of this processing must then be able to be communicated back to the proper recipient in cases where a response is required or a conflict exists between safe navigational practice and the intentions of the other vessel as communicated or observed.

5.4 Testing Metrics and Certification

Before allowing autonomous marine vehicles to operate in the vicinity of manned vessels, each AMV should undergo a rigorous certification process including:

- testing[4] of collision avoidance scenarios including Rules 11-18,
- verification of correct lights including the unmanned vehicle signal device discussed above,
- testing and verification of sound receiving and transmitting devices including compliance with the applicable rules, and
- verification of communication capabilities including but not limited to AIS, VHF radio, observing and signaling with day shapes, receiving and issuing sound signals such as the ship's whistle, and other signals as might be deemed appropriate.

5.5 Recommended Changes to COLREGS

Several sections of COLREGS use language that is specific to manned vessels. This study recommends that many areas can have their language changed slightly to incor-

[4]Testing of autonomous marine vehicles to show compliance with COLREGS is ongoing work of the author.

porate the use of autonomous vessels in the manned environment. Specific examples follow.

Rule 4 Modify Rule 4 to indicate that autonomous vessels with certified "sight and hearing" devices such as cameras, radar, and above-water acoustic sensors shall be deemed in compliance with the Rules.

> Existing:
>
> "Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision."

> Suggested Modification:
>
> "Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision. For the purposes of these Rules, an unmanned vessel which has been certified for safe operations by the cognizant authority shall be deemed to have a proper look-out by sight and hearing if her visual and above-water acoustic detection systems are operating to levels required by the certifying authority."

Rule 11 Expand Rule 11 to amplify the word "sight" as to allow for visual detection using camera-based sensors for unmanned vessels. This amplification should apply to all subsequent rules in the section of powered vessel rules.

Existing:

“Rules in this section apply to vessels in sight of one another.”

Suggested Modification:

“Rules in this section apply to vessels in sight of one another. A vessel as viewed by an unmanned vessel which has been certified for safe operations by the cognizant authority shall be deemed to be in sight of the unmanned vessel if a look-out of a manned vessel of similar size to the unmanned vessel would normally sight and recognize the vessel.”

Rule 32 Modify Rule 32 to address vessels in sight of one another for the purposes of autonomous marine vehicles. Rule 32 is the governing rule for definitions used through the “Part D – Sounds and Light Signals” of COLREGS which includes Rule 32 through Rule 37. The rules in Part D of COLREGS require amplification as to what “in sight” means to an autonomous marine vehicle. The detailed rules such as Rule 34 – Maneuvering and Warning Signals, for example, would then be sufficient as written.

Existing:

“(a) The word ‘whistle’ means any sound signaling appliance capable of producing the prescribed blasts and which complies with the specifications in Annex III to these [Regulations — Rules].

(b) The term 'short blast' means a blast of about one second's duration.

(c) The term 'prolonged blast' means a blast of from four to six seconds' duration."

Suggested Modification:

"(a) The word 'whistle' means any sound signaling appliance capable of producing the prescribed blasts and which complies with the specifications in Annex III to these [Regulations — Rules].

(b) The term 'short blast' means a blast of about one second's duration.

(c) The term 'prolonged blast' means a blast of from four to six seconds' duration.

(d) For the purposes of these Rules, a vessel as viewed by an unmanned vessel which has been certified for safe operations by the cognizant authority shall be deemed to be in sight of the unmanned vessel if a look-out of a manned vessel of similar size to the unmanned vessel would normally sight and recognize the vessel."

5.6 Certification Authority

This study recommends that certification authority for autonomous marine vehicles should be held by the same organization in each country that certified manned vessels. By having a separate organization or delegated authority, the intention of full integration would be hindered. For example, in the United States, the US Coast

Guard certifies manned vessels as being safety compliant for operations. This by extension should be the same certifying authority to show that operations of an AMV are sufficiently safe to comply with the Rules as well as navigate safely both on the open ocean as well as in and out of harbor.

The certification of both safety and compliance level should be achieved in a grading system that checks for the following:

- observability of standard shapes and markers (e.g., buoys, day markers, day shapes, etc.),
- recognition of various types of vessels at ranges at least as good as a look-out with reasonable equipment such as binoculars,
- correct determination of when another vessel is at risk of collision and therefore in need of action in accordance with the Rules,
- given a risk of collision, correct determination of the appropriate rule,
- given determination of an appropriate rule, correct maneuver in accordance with the Rules, and
- safe and reasonable actions in accordance with the Rules as to behave as safe or safer than a reasonable master of a manned vessel of similar dimensions.

By having appropriate certification by the designated Administrator of the country who flags the vessel, both accountability and responsibility for certification can be assigned to the government of each nation authorizing its flag to be flown from autonomous marine vehicles. Further, this certification can be used by insurance organizations such as Lloyd's of London as a metric before issuing a policy to the owners of autonomous marine vehicles.

Chapter 6

Conclusions

This thesis examined the application of the internationally recognized collision avoidance regulations to autonomous marine vehicles. The major collision avoidance parameters that would normally be seen in any collision avoidance technique that is interested in balancing both safety and efficiency were studied using a design of experiments with a central composite design and regression analysis.

With the analysis provided in this study, writers of autonomy software for collision avoidance will now be able to find an appropriate balance of safety and efficiency given the magnitude of risk aversion for the platform at hand. For example, an autonomous merchant traveling with dangerous cargo might desire reduced efficiency for heightened safety whereas a Coast Guard autonomous intercept vessel might require minimal ranges at CPA while desiring a high efficiency to minimize time to intercept a threat. Appropriate selection of the relevant collision avoidance parameters using the results of the regression analysis in this study could help shape an appropriate selection for each mission.

The regression analysis showed that the average efficiency was highly dependent on the distance at which an AMV was allowed to start taking action for another contact where a risk of collision existed. The second most important factor was the desired range at CPA while the relative speeds studied were not statistically significant. The standard deviation of efficiency followed with similar results. Safety was measured using a collision fraction defined by the ratio of collision range violations to total number of encounters. The regression analysis showed that the collision fraction measurement of safety was most impacted by the same variable that was most influential for efficiency: the distance at which action could first be taken. The safety and efficiency effects by this factor were of opposite sign; that is, taking action early resulted in high safety but lower efficiency. This study found the impact of other non-primary but still statistically significant parameters on each of the three primary response variables. For autonomous marine vehicles it seems that the common knowledge of vessel masters remains true: take action early to avoid a collision.

A professionally interesting result of the regression analysis was that the protocol based COLREGS collision avoidance behavior showed improved overall safety for the parameter ranges studied while holding efficiency near constant. The cases where the COLREGS-based approach performed worse than the non-protocol based algorithm all shared one thing in common: the range at which action could first be taken was very small. This warrants further study to see if a possible improvement to the algorithm could drive this region of the tradespace to have improved performance of the COLREGS algorithm over the non-protocol based algorithm. An example study might consider whether taking action as the stand on vessel in accordance with rule 17(a)(ii) might be warranted earlier than currently allowed by the algorithm.

The high volume of simulation data produced by this study allows for a high degree of confidence in the regression analysis results. Extensive robustness testing included up to seven (7) simulated vehicles operating in COLREGS situations with each other simultaneously. A further major step in this thesis was to test these autonomous COLREGS algorithms on real-world vessels. These autonomous COLREGS algorithms were demonstrated using up to five (5) autonomous marine vehicles concurrently on the Charles River at the MIT Autonomy Laboratory in Cambridge, MA. This is the largest known demonstration of simultaneous autonomous COLREGS collision avoidance to date. The testing was done using multiple rules with multiple vehicles concurrently including scenarios with simultaneous head on, overtaking, and crossing decisions being made at once which proved that the complexities required of a manned vessel master could indeed be realized on an autonomous platform.

Appendix A

Regression Framework

The general process for MATLAB processing included the following:

setDirectory.m Set the global variables for use by the other scripts.

processFolders.m Determined which experiments were completed and listed incomplete experiments. Each experiment was contained in its own folder labeled with the flags for experimental settings allowing for quick assessment of which experiments were complete and which required experimentation.

batchProcessData.m Processed the completed experiments as determined by processFolders.m by reading *.adata, *.cdata, and *.tdata files then performing statistical analysis. Created charts which were automatically saved as PDFs as shown in Figure 2-20 .

processAssimilatedData.m Added the experimental statistics to a common file for aggregate processing. Saved file to a *.rdata file.

batchProcessRData.m Analyzed the *.rdata files and created charts for meta-analysis.

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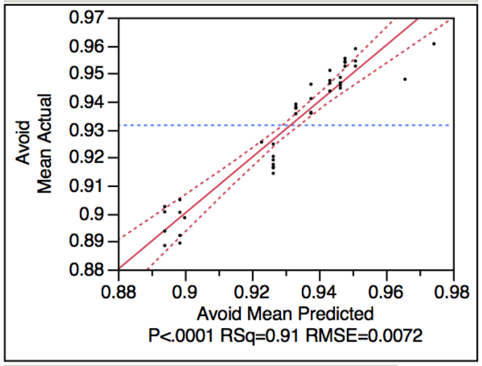
Appendix B

Regression Results

Response Avoid Mean

Actual by Predicted Plot



Summary of Fit

RSquare	0.908131
RSquare Adj	0.89282
Root Mean Square Error	0.007193
Mean of Response	0.931479
Observations (or Sum Wgts)	43

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	0.01841211	0.003069	59.3107
Error	36	0.00186261	0.000052	**Prob > F**
C. Total	42	0.02027472		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	8	0.00143447	0.000179	11.7265
Pure Error	28	0.00042814	0.000015	**Prob > F**
Total Error	36	0.00186261		<.0001*
				Max RSq
				0.9789

Figure B-1: Regression analysis results for COLREGs mean efficiency.

colregs_regression_analysis_CCD 2: Fit Least Squares **Page 2 of 2**

Response Avoid Mean

Lack Of Fit

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9263738	0.001944	476.45	<.0001*
pwt outer	-0.015639	0.001093	-14.31	<.0001*
cpa max	-0.009002	0.001093	-8.24	<.0001*
pwt outer*pwt outer	0.0019016	0.001019	1.87	0.0703
pwt outer*cpa max	-0.010563	0.001272	-8.31	<.0001*
cpa max*cpa max	0.0031665	0.001019	3.11	0.0037*
pwt outer*relative speed	-0.002258	0.001272	-1.78	0.0842

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.015639	0.001093	-14.31	<.0001*
pwt outer*cpa max	-0.010563	0.001272	-8.31	<.0001*
cpa max	-0.009002	0.001093	-8.24	<.0001*
cpa max*cpa max	0.0031665	0.001019	3.11	0.0037*
pwt outer*pwt outer	0.0019016	0.001019	1.87	0.0703
pwt outer*relative speed	-0.002258	0.001272	-1.78	0.0842

Prediction Profiler

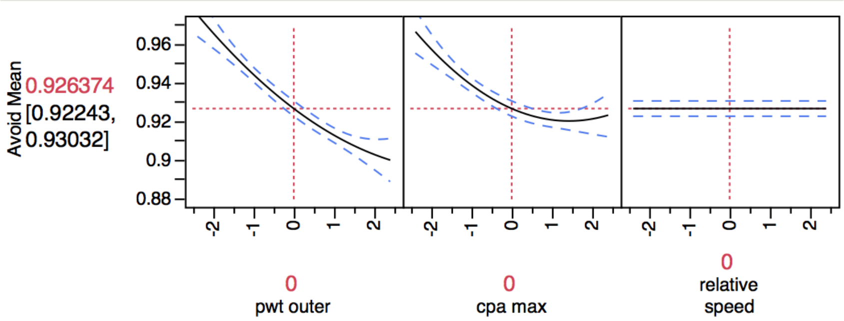
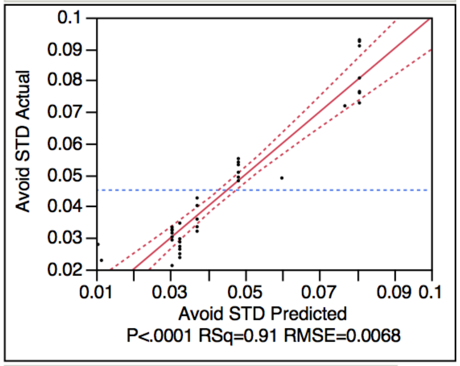


Figure B-2: Regression analysis results for COLREGs mean efficiency.

Response Avoid STD

Actual by Predicted Plot



Summary of Fit

RSquare	0.910817
RSquare Adj	0.898766
Root Mean Square Error	0.006764
Mean of Response	0.045166
Observations (or Sum Wgts)	43

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	0.01728635	0.003457	75.5757
Error	37	0.00169259	0.000046	**Prob > F**
C. Total	42	0.01897894		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	3	0.00089016	0.000297	12.5724
Pure Error	34	0.00080243	0.000024	**Prob > F**
Total Error	37	0.00169259		<.0001*
				Max RSq
				0.9577

Figure B-3: Regression analysis results for COLREGs standard deviation of efficiency.

colregs_regression_analysis_CCD.jmp: Fit Least Squares **Page 2 of 2**

Response Avoid STD

Lack Of Fit

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.0482081	0.001828	26.37	<.0001*
pwt outer	0.0137428	0.001028	13.37	<.0001*
cpa max	0.0103814	0.001028	10.10	<.0001*
pwt outer*pwt outer	-0.000721	0.000959	-0.75	0.4566
pwt outer*cpa max	0.0114188	0.001196	9.55	<.0001*
cpa max*cpa max	-0.002299	0.000959	-2.40	0.0216*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	0.0137428	0.001028	13.37	<.0001*
cpa max	0.0103814	0.001028	10.10	<.0001*
pwt outer*cpa max	0.0114188	0.001196	9.55	<.0001*
cpa max*cpa max	-0.002299	0.000959	-2.40	0.0216*
pwt outer*pwt outer	-0.000721	0.000959	-0.75	0.4566

Prediction Profiler

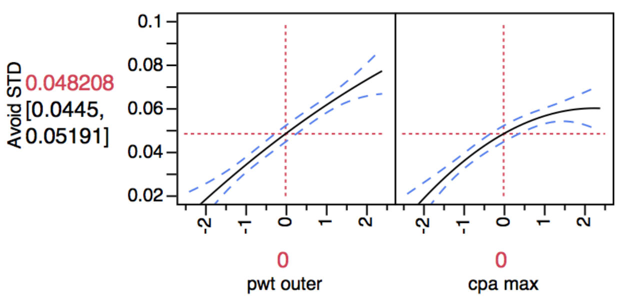
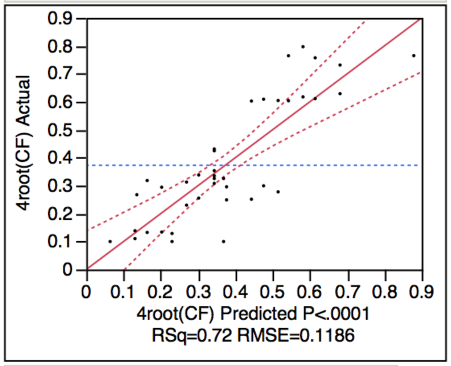


Figure B-4: Regression analysis results for COLREGs standard deviation of efficiency.

Least Squares Fit

Response 4root(CF)

Actual by Predicted Plot



Summary of Fit

RSquare	0.724327
RSquare Adj	0.687073
Root Mean Square Error	0.118628
Mean of Response	0.372645
Observations (or Sum Wgts)	43

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	1.3680955	0.273619	19.4434
Error	37	0.5206873	0.014073	**Prob > F**
C. Total	42	1.8887828		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	19	0.23954224	0.012607	0.8072
Pure Error	18	0.28114502	0.015619	**Prob > F**
Total Error	37	0.52068726		0.6767
				Max RSq
				0.8512

Figure B-5: Regression analysis results for COLREGs collision frequency.

colregs_regression_analysis_CCD 2: Fit Least Squares Page 2 of 3

Least Squares Fit

Response 4root(CF)

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3434983	0.024493	14.02	<.0001*
pwt outer	-0.156195	0.018025	-8.67	<.0001*
pwt outer*pwt outer	0.028936	0.016393	1.77	0.0858
pwt outer*cpa min	-0.06913	0.020971	-3.30	0.0022*
pwt inner*cpa min	-0.033361	0.020971	-1.59	0.1202
pwt inner*cpa max	-0.049685	0.020971	-2.37	0.0232*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
pwt outer	1	1	1.0567143	75.0900	<.0001*
pwt outer*pwt outer	1	1	0.0438483	3.1159	0.0858
pwt outer*cpa min	1	1	0.1529250	10.8668	0.0022*
pwt inner*cpa min	1	1	0.0356136	2.5307	0.1202
pwt inner*cpa max	1	1	0.0789944	5.6133	0.0232*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.156195	0.018025	-8.67	<.0001*
pwt outer*cpa min	-0.06913	0.020971	-3.30	0.0022*
pwt inner*cpa max	-0.049685	0.020971	-2.37	0.0232*
pwt outer*pwt outer	0.028936	0.016393	1.77	0.0858
pwt inner*cpa min	-0.033361	0.020971	-1.59	0.1202

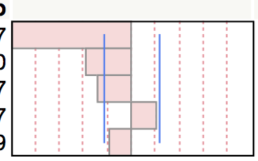
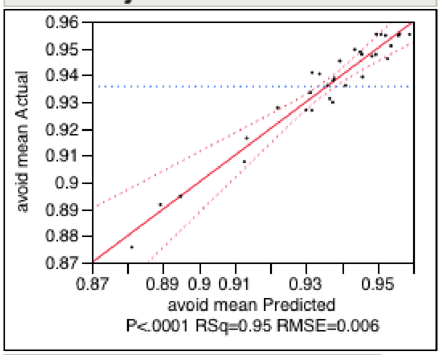


Figure B-6: Regression analysis results for COLREGs collision frequency.

Response avoid mean

Actual by Predicted Plot



Summary of Fit

RSquare	0.947426
RSquare Adj	0.909455
Root Mean Square Error	0.005969
Mean of Response	0.935834
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	0.01155633	0.000889	24.9518
Error	18	0.00064128	0.000036	**Prob > F**
C. Total	31	0.01219761		<.0001*

Figure B-7: Regression analysis results for CPA mean efficiency.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9358341	0.001055	886.92	<.0001*
pwt outer	-0.006832	0.001055	-6.48	<.0001*
cpa max	-0.00853	0.001055	-8.08	<.0001*
pwt outer*cpa max	-0.011139	0.001055	-10.56	<.0001*
pwt outer*cpa min	0.0047166	0.001055	4.47	0.0003*
cpa min	0.0037541	0.001055	3.56	0.0022*
cpa min*cpa max	0.0042397	0.001055	4.02	0.0008*
pwt inner	-0.003717	0.001055	-3.52	0.0024*
pwt outer*cpa max*relative speed	-0.003537	0.001055	-3.35	0.0036*
cpa max*relative speed	-0.00309	0.001055	-2.93	0.0090*
pwt outer*pwt inner*cpa min*cpa max	0.0030441	0.001055	2.88	0.0099*
pwt inner*cpa min	0.0027147	0.001055	2.57	0.0192*
pwt inner*relative speed	0.0026347	0.001055	2.50	0.0224*
pwt outer*cpa min*cpa max	0.0019622	0.001055	1.86	0.0794

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
pwt outer	1	1	0.00149372	41.9270	<.0001*
cpa max	1	1	0.00232852	65.3589	<.0001*
pwt outer*cpa max	1	1	0.00397052	111.4479	<.0001*
pwt outer*cpa min	1	1	0.00071187	19.9814	0.0003*
cpa min	1	1	0.00045098	12.6584	0.0022*
cpa min*cpa max	1	1	0.00057520	16.1452	0.0008*
pwt inner	1	1	0.00044201	12.4067	0.0024*
pwt outer*cpa max*relative speed	1	1	0.00040023	11.2341	0.0036*
cpa max*relative speed	1	1	0.00030560	8.5779	0.0090*
pwt outer*pwt inner*cpa min*cpa max	1	1	0.00029652	8.3230	0.0099*
pwt inner*cpa min	1	1	0.00023582	6.6193	0.0192*
pwt inner*relative speed	1	1	0.00022213	6.2349	0.0224*
pwt outer*cpa min*cpa max	1	1	0.00012321	3.4582	0.0794

Figure B-8: Regression analysis results for CPA mean efficiency.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer*cpa max	-0.011139	0.001055	-10.56	<.0001*
cpa max	-0.00853	0.001055	-8.08	<.0001*
pwt outer	-0.006832	0.001055	-6.48	<.0001*
pwt outer*cpa min	0.0047166	0.001055	4.47	0.0003*
cpa min*cpa max	0.0042397	0.001055	4.02	0.0008*
cpa min	0.0037541	0.001055	3.56	0.0022*
pwt inner	-0.003717	0.001055	-3.52	0.0024*
pwt outer*cpa max*relative speed	-0.003537	0.001055	-3.35	0.0036*
cpa max*relative speed	-0.00309	0.001055	-2.93	0.0090*
pwt outer*pwt inner*cpa min*cpa max	0.0030441	0.001055	2.88	0.0099*
pwt inner*cpa min	0.0027147	0.001055	2.57	0.0192*
pwt inner*relative speed	0.0026347	0.001055	2.50	0.0224*
pwt outer*cpa min*cpa max	0.0019622	0.001055	1.86	0.0794

Prediction Profiler

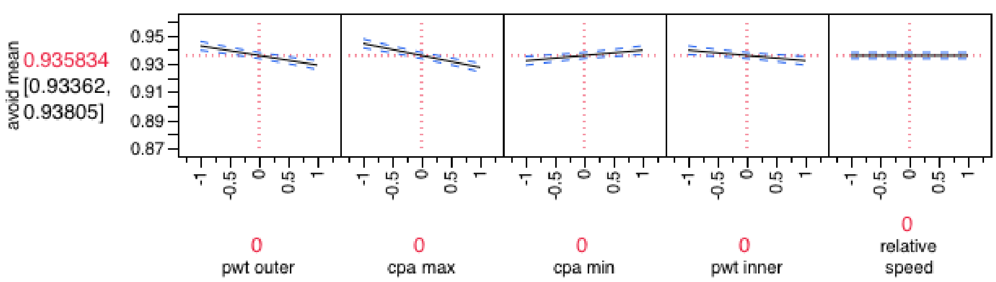
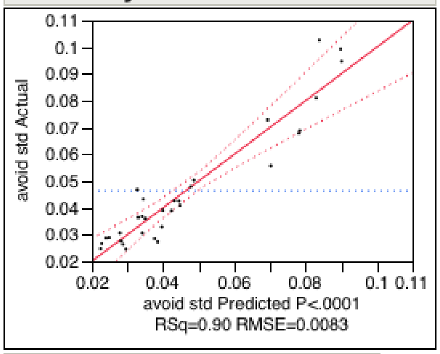


Figure B-9: Regression analysis results for CPA mean efficiency.

Response avoid std

Actual by Predicted Plot



Summary of Fit

RSquare	0.90008
RSquare Adj	0.865325
Root Mean Square Error	0.008284
Mean of Response	0.046307
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	0.01421854	0.001777	25.8981
Error	23	0.00157843	0.000069	**Prob > F**
C. Total	31	0.01579697		<.0001*

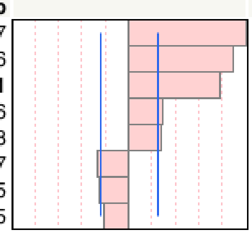
Figure B-10: Regression analysis results for CPA standard deviation of efficiency.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.0463071	0.001464	31.62	<.0001*
pwt outer	0.009976	0.001464	6.81	<.0001*
pwt inner	0.0037424	0.001464	2.56	0.0177*
cpa max	0.0113708	0.001464	7.76	<.0001*
pwt outer*cpa max	0.0126899	0.001464	8.67	<.0001*
cpa max*relative speed	0.0034823	0.001464	2.38	0.0261*
pwt inner*relative speed	-0.003332	0.001464	-2.27	0.0325*
pwt outer*pwt inner*cpa min*cpa max	-0.003145	0.001464	-2.15	0.0425*
pwt outer*cpa min	-0.002713	0.001464	-1.85	0.0768

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer*cpa max	0.0126899	0.001464	8.67	<.0001*
cpa max	0.0113708	0.001464	7.76	<.0001*
pwt outer	0.009976	0.001464	6.81	<.0001*
pwt inner	0.0037424	0.001464	2.56	0.0177*
cpa max*relative speed	0.0034823	0.001464	2.38	0.0261*
pwt inner*relative speed	-0.003332	0.001464	-2.27	0.0325*
pwt outer*pwt inner*cpa min*cpa max	-0.003145	0.001464	-2.15	0.0425*
pwt outer*cpa min	-0.002713	0.001464	-1.85	0.0768



Prediction Profiler

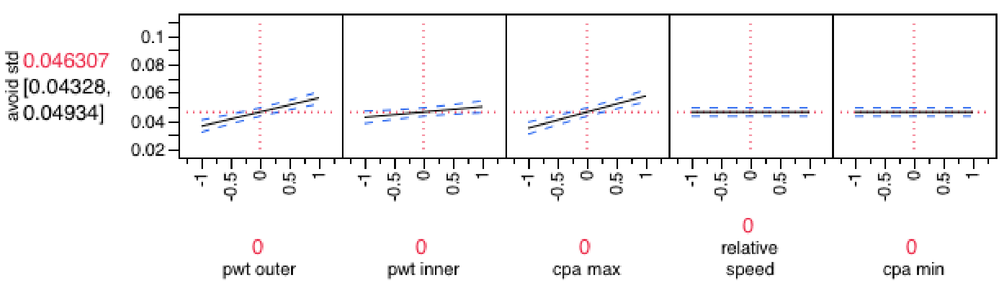
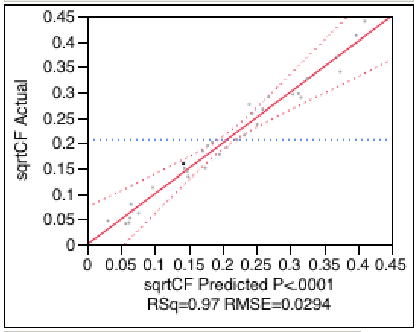


Figure B-11: Regression analysis results for CPA standard deviation of efficiency.

Response sqrtCF

Actual by Predicted Plot



Summary of Fit

RSquare	0.971808
RSquare Adj	0.924822
Root Mean Square Error	0.029444
Mean of Response	0.206343
Observations (or Sum Wgts)	33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	20	0.35862206	0.017931	20.6828
Error	12	0.01040346	0.000867	**Prob > F**
C. Total	32	0.36902552		<.0001*

Figure B-12: Regression analysis results for CPA collision frequency.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.2063428	0.005126	40.26	<.0001*
pwt outer	-0.06741	0.005205	-12.95	<.0001*
pwt inner	-0.020256	0.005205	-3.89	0.0021*
pwt outer*pwt inner	0.0145817	0.005205	2.80	0.0160*
cpa min	-0.013166	0.005205	-2.53	0.0264*
pwt outer*cpa min	-0.021892	0.005205	-4.21	0.0012*
pwt inner*cpa min	-0.011188	0.005205	-2.15	0.0527
pwt outer*pwt inner*cpa min	0.022714	0.005205	4.36	0.0009*
cpa max	0.0114931	0.005205	2.21	0.0474*
pwt outer*cpa max	0.0138854	0.005205	2.67	0.0205*
pwt inner*cpa max	-0.03176	0.005205	-6.10	<.0001*
pwt outer*pwt inner*cpa max	0.0212119	0.005205	4.08	0.0015*
cpa min*cpa max	-0.018799	0.005205	-3.61	0.0036*
pwt outer*cpa min*cpa max	0.0109198	0.005205	2.10	0.0578
pwt outer*pwt inner*cpa min*cpa max	-0.017057	0.005205	-3.28	0.0066*
pwt inner*relative speed	-0.020047	0.005205	-3.85	0.0023*
pwt outer*pwt inner*relative speed	0.0146607	0.005205	2.82	0.0156*
cpa min*relative speed	0.0101337	0.005205	1.95	0.0753
pwt outer*pwt inner*cpa min*relative speed	-0.012371	0.005205	-2.38	0.0350*
cpa max*relative speed	0.0303135	0.005205	5.82	<.0001*
pwt outer*cpa max*relative speed	0.0201902	0.005205	3.88	0.0022*

Figure B-13: Regression analysis results for CPA collision frequency.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
pwt outer	-0.06741	0.005205	-12.95	<.0001*
pwt inner*cpa max	-0.03176	0.005205	-6.10	<.0001*
cpa max*relative speed	0.0303135	0.005205	5.82	<.0001*
pwt outer*pwt inner*cpa min	0.022714	0.005205	4.36	0.0009*
pwt outer*cpa min	-0.021892	0.005205	-4.21	0.0012*
pwt outer*pwt inner*cpa max	0.0212119	0.005205	4.08	0.0015*
pwt inner	-0.020256	0.005205	-3.89	0.0021*
pwt outer*cpa max*relative speed	0.0201902	0.005205	3.88	0.0022*
pwt inner*relative speed	-0.020047	0.005205	-3.85	0.0023*
cpa min*cpa max	-0.018799	0.005205	-3.61	0.0036*
pwt outer*pwt inner*cpa min*cpa max	-0.017057	0.005205	-3.28	0.0066*
pwt outer*pwt inner*relative speed	0.0146607	0.005205	2.82	0.0156*
pwt outer*pwt inner	0.0145817	0.005205	2.80	0.0160*
pwt outer*cpa max	0.0138854	0.005205	2.67	0.0205*
cpa min	-0.013166	0.005205	-2.53	0.0264*
pwt outer*pwt inner*cpa min*relative speed	-0.012371	0.005205	-2.38	0.0350*
cpa max	0.0114931	0.005205	2.21	0.0474*
pwt inner*cpa min	-0.011188	0.005205	-2.15	0.0527
pwt outer*cpa min*cpa max	0.0109198	0.005205	2.10	0.0578
cpa min*relative speed	0.0101337	0.005205	1.95	0.0753

Prediction Profiler

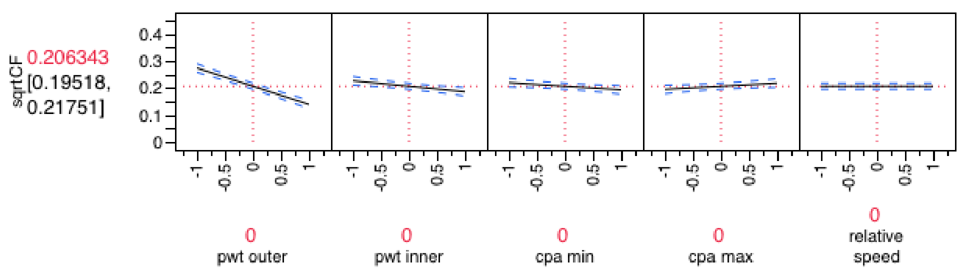
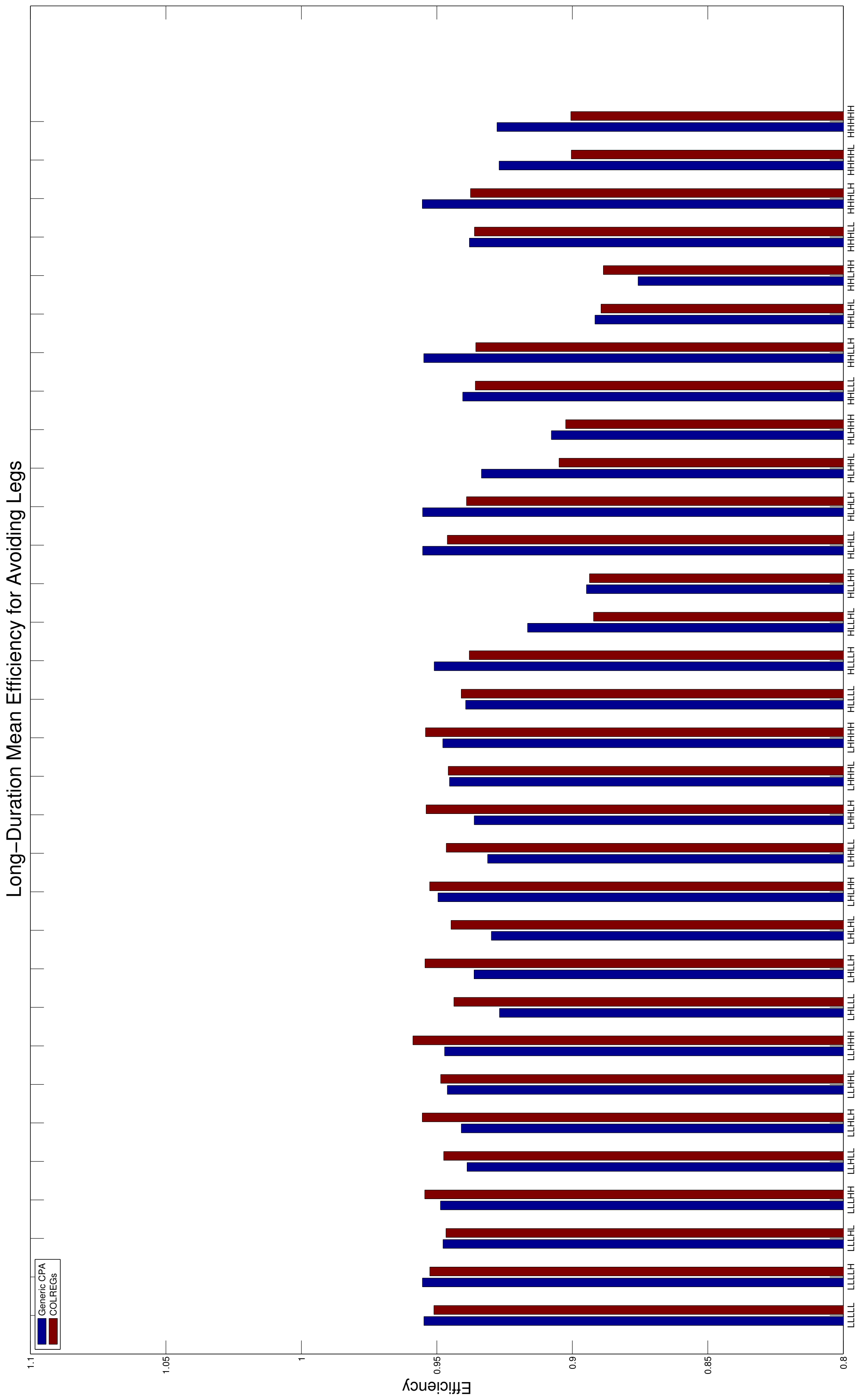


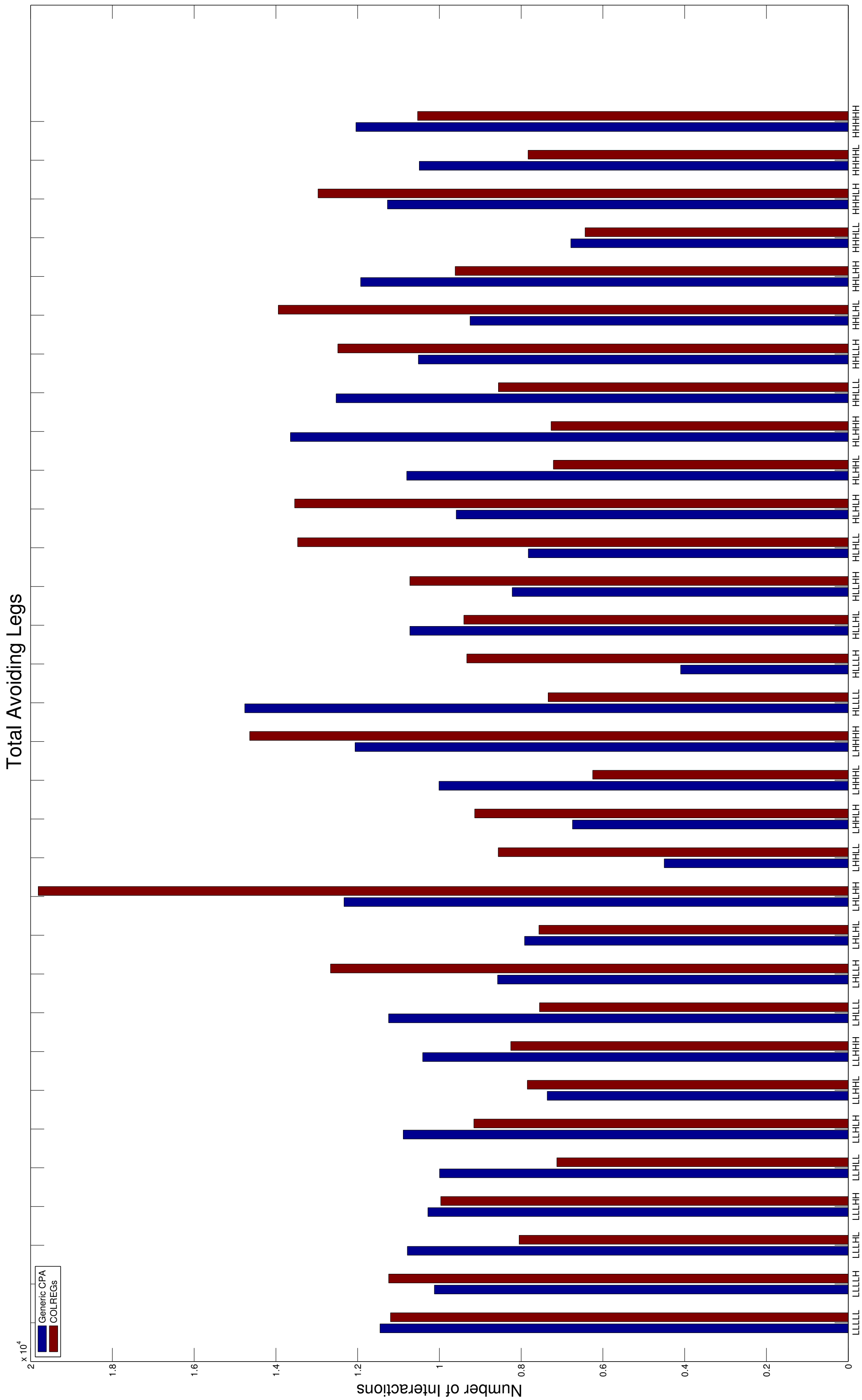
Figure B-14: Regression analysis results for CPA collision frequency.

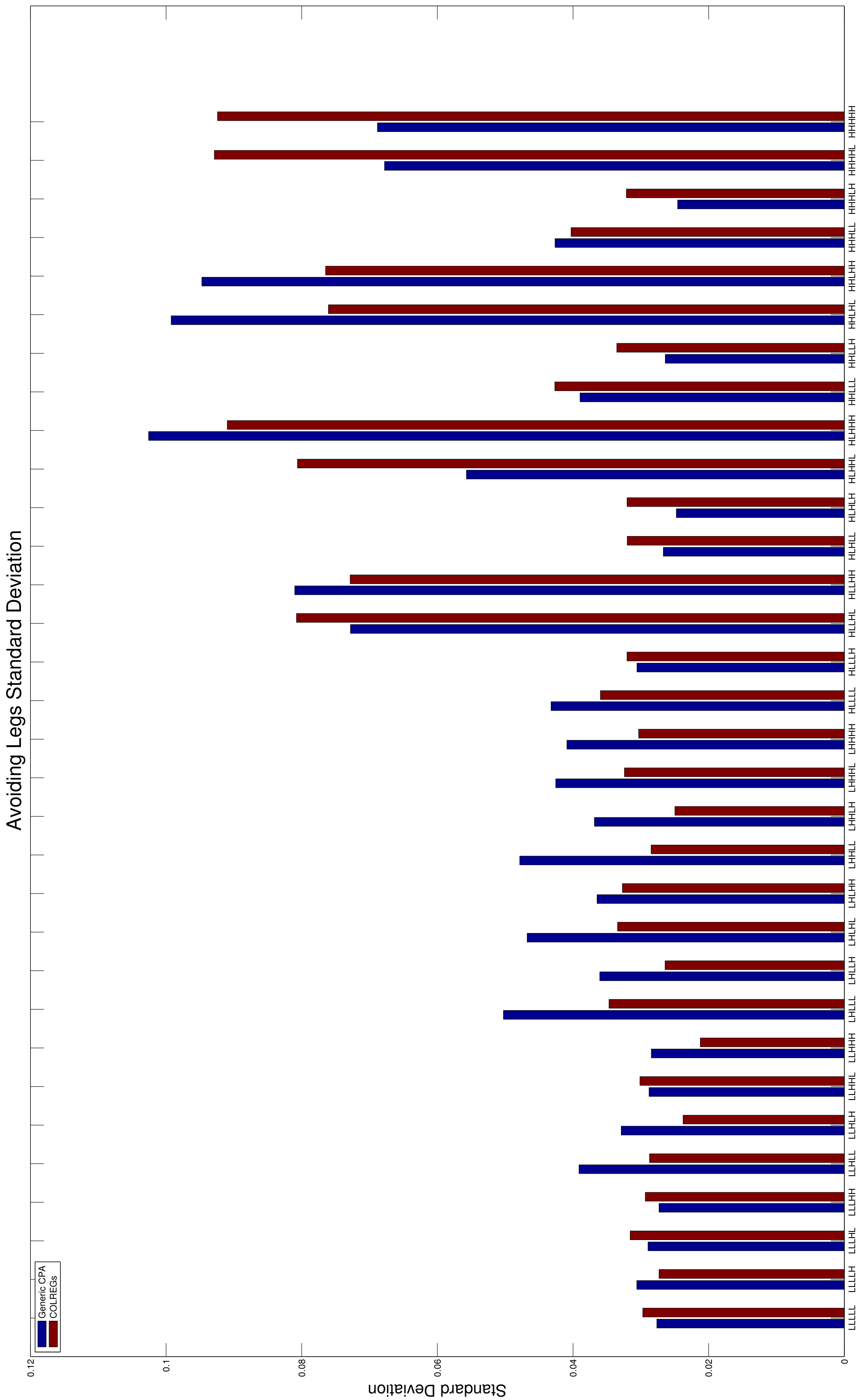
Appendix C

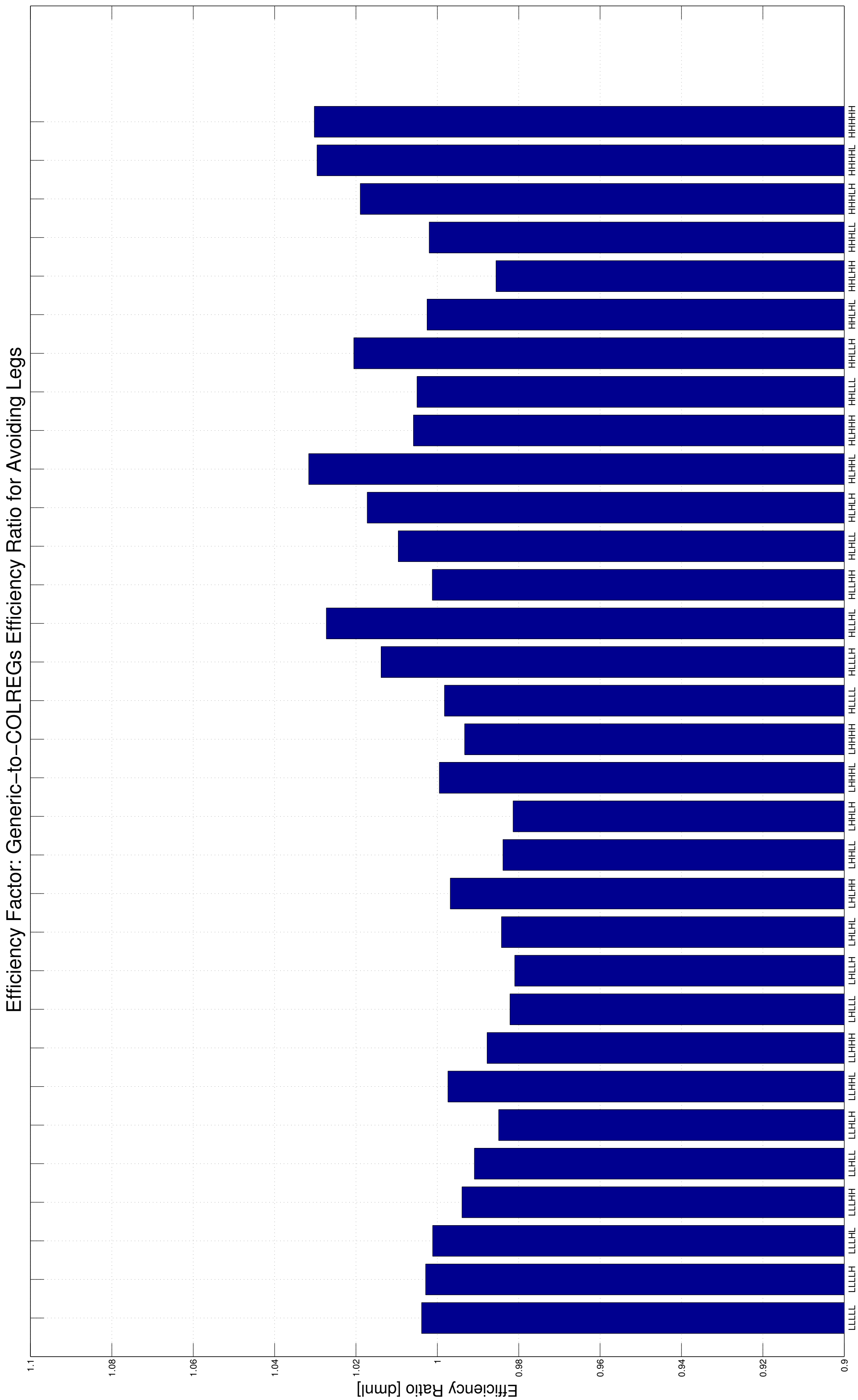
Graphical Results of Experimentation

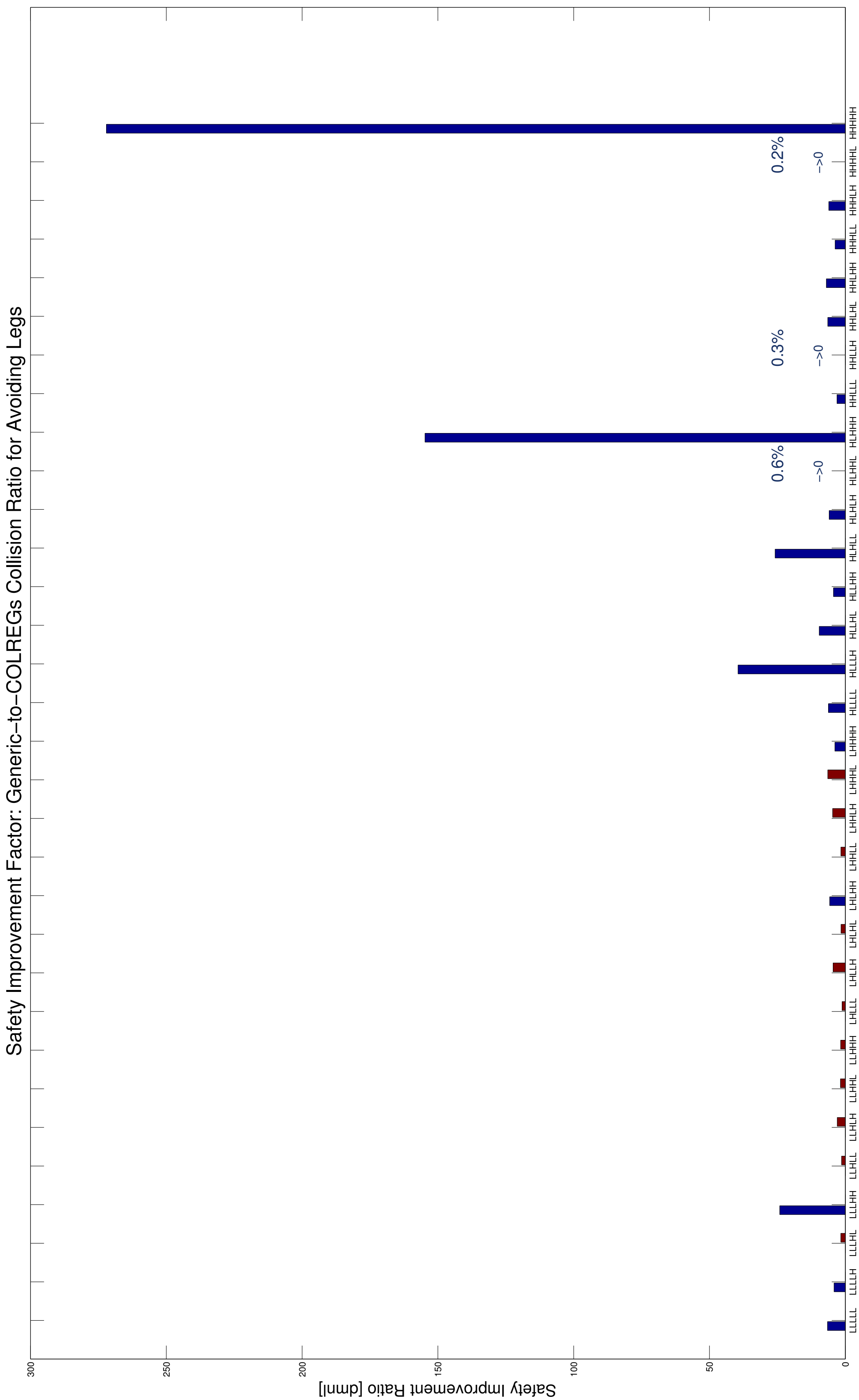


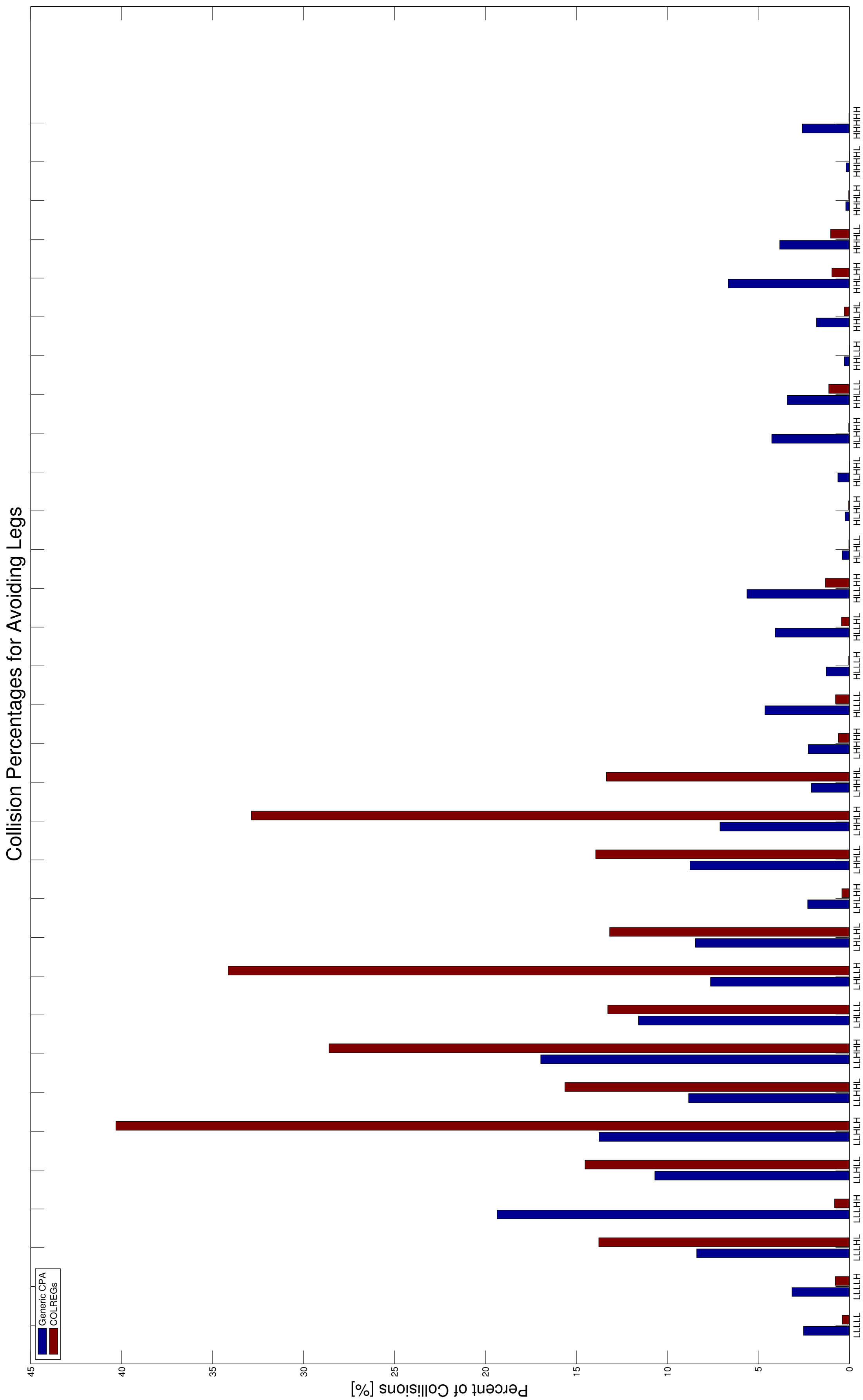
Long−Duration Mean Efficiency for Avoiding Legs
Efficiency
0.8
0.85
0.9
0.95
1
1.05
1.1
Generic CPA
COLREGs
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH

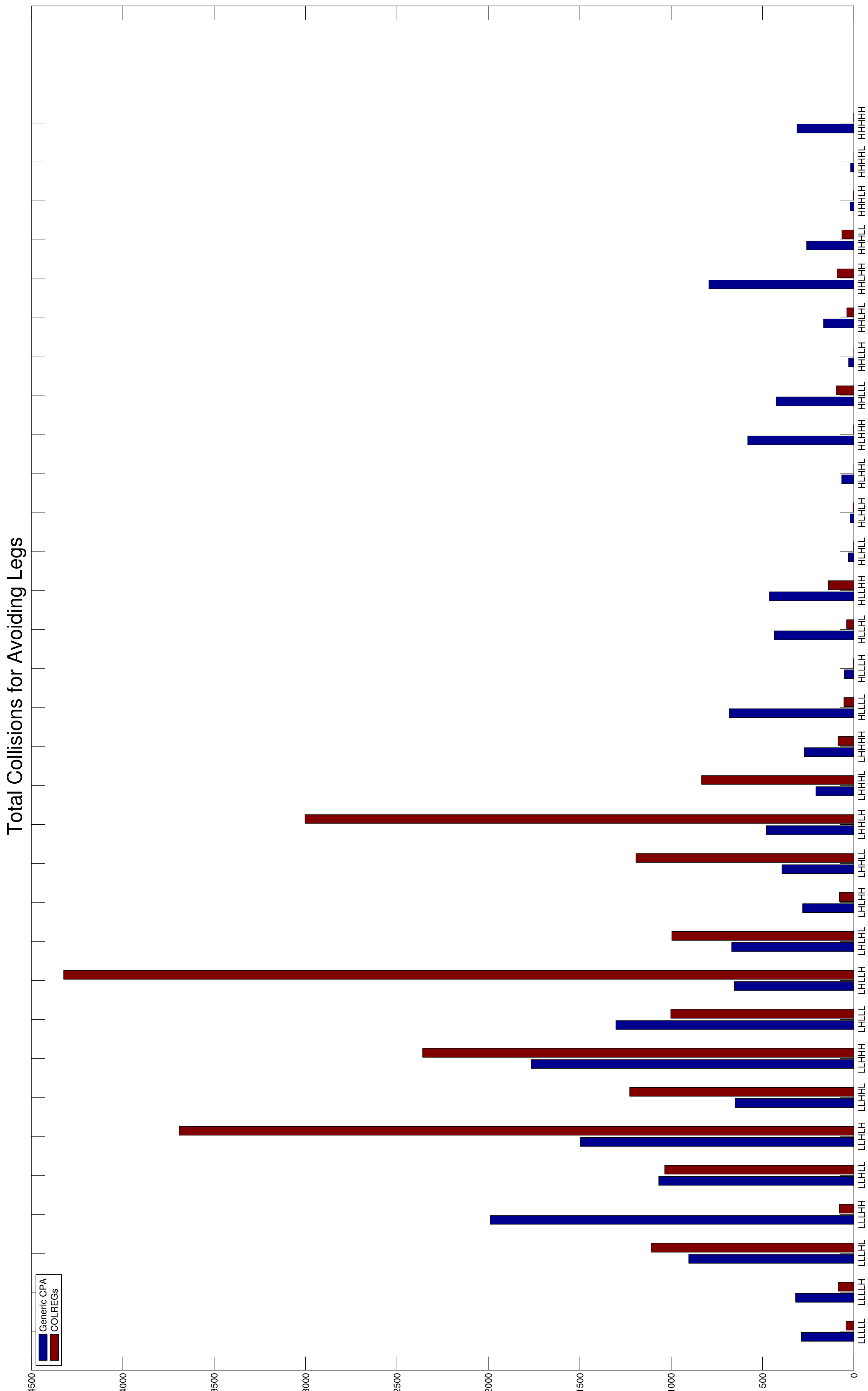

Total Avoiding Legs
Number of Interactions
x 10^4
Generic CPA
COLREGs
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH

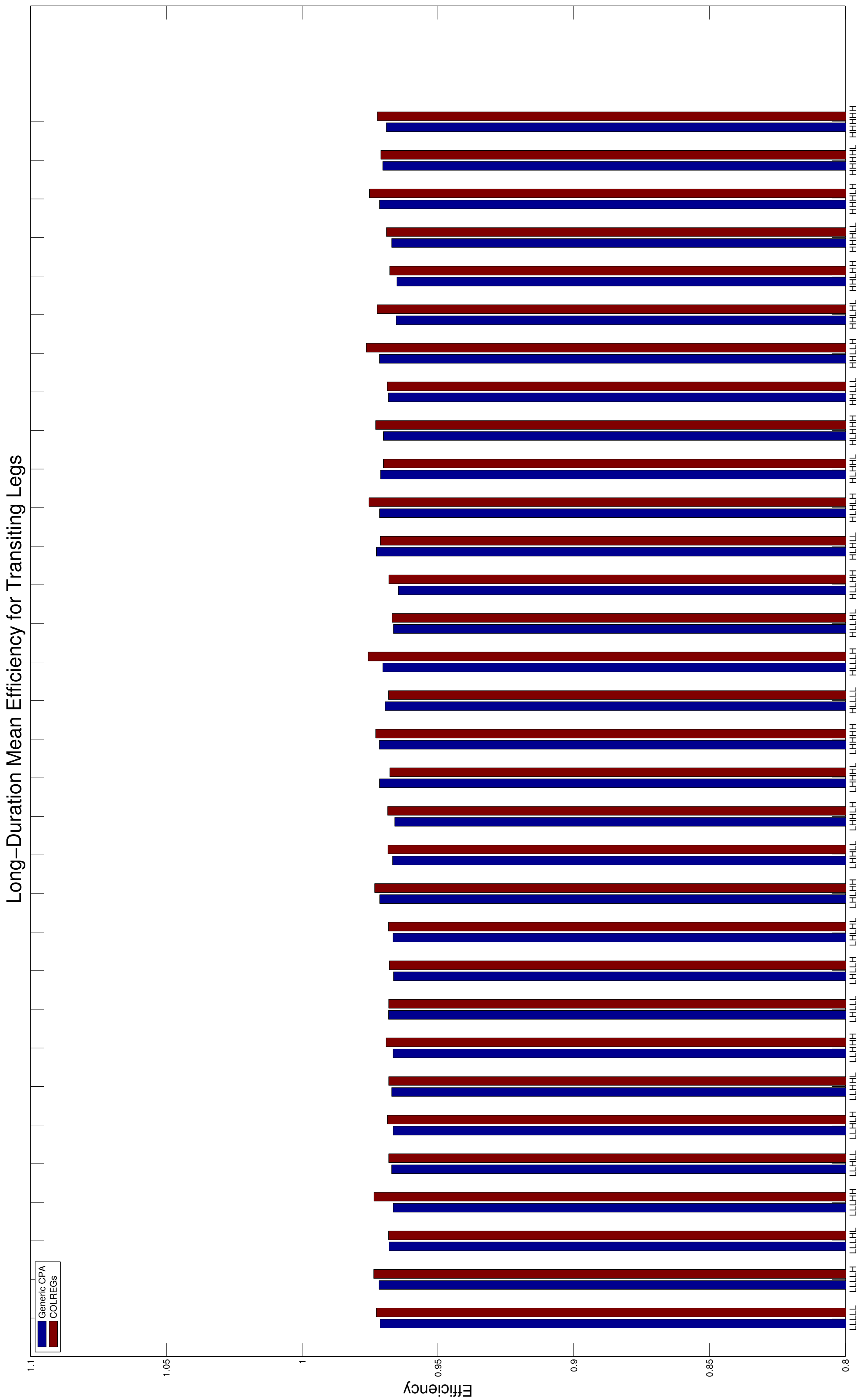

Avoiding Legs Standard Deviation
Generic CPA
COLREGs
Standard Deviation
0
0.02
0.04
0.06
0.08
0.1
0.12
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH

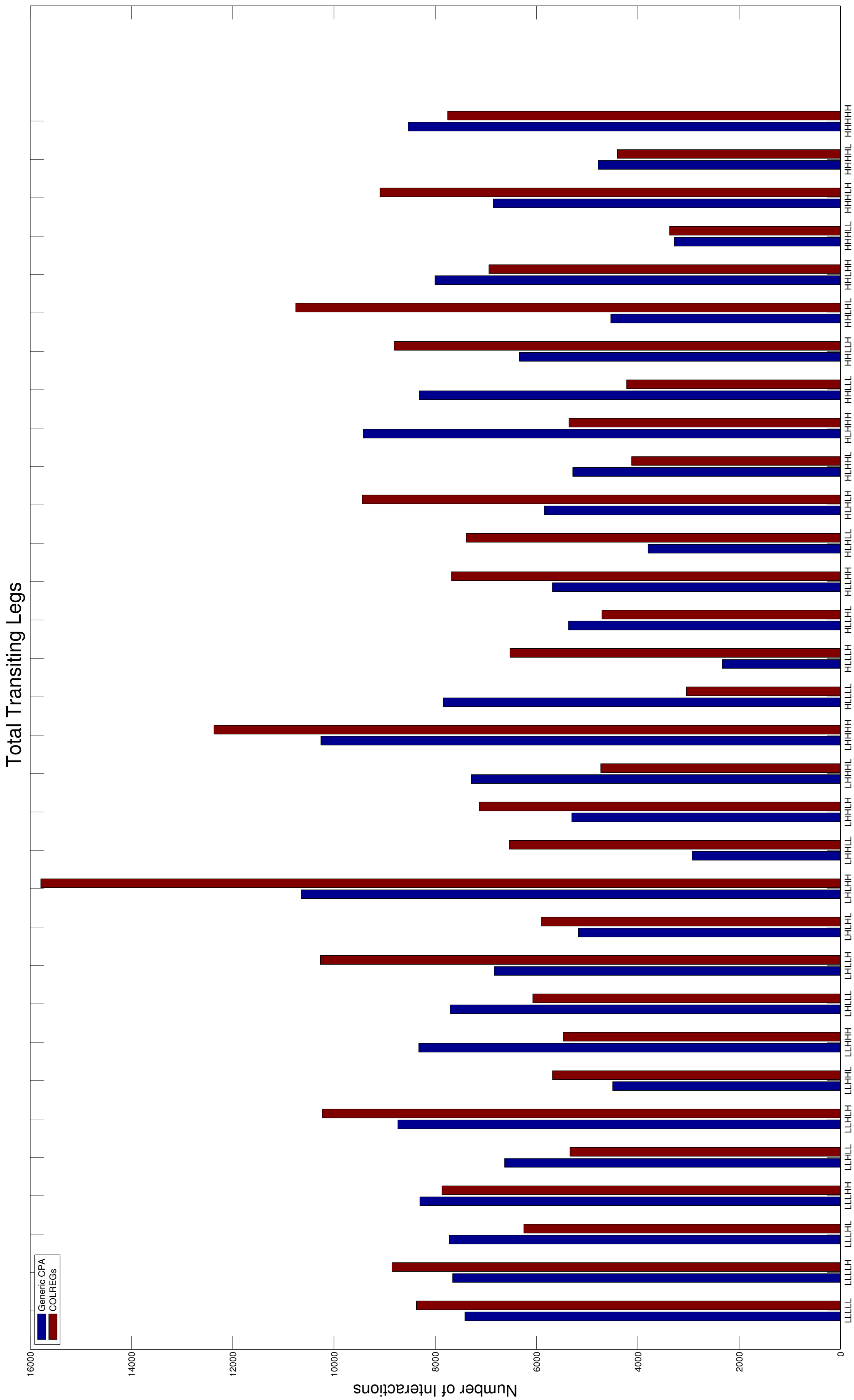

Efficiency Factor: Generic−to−COLREGs Efficiency Ratio for Avoiding Legs
Efficiency Ratio [dmnl]
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH


Safety Improvement Factor: Generic−to−COLREGs Collision Ratio for Avoiding Legs
Safety Improvement Ratio [dmnl]
0
50
100
150
200
250
300
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH
−>0
0.6%
−>0
0.3%
−>0
0.2%


Collision Percentages for Avoiding Legs
Generic CPA
COLREGs
Percent of Collisions [%]
0
5
10
15
20
25
30
35
40
45
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH


Total Collisions for Avoiding Legs
Generic CPA
COLREGs
Number of Collisions
0
500
1000
1500
2000
2500
3000
3500
4000
4500
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH


Long−Duration Mean Efficiency for Transiting Legs
Efficiency
1.1
1.05
1
0.95
0.9
0.85
0.8
Generic CPA
COLREGs
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
LHHHL
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH



Total Transiting Legs
Generic CPA
COLREGs
Number of Interactions
0
2000
4000
6000
8000
10000
12000
14000
16000
LLLLL
LLLLH
LLLHL
LLLHH
LLHLL
LLHLH
LLHHL
LLHHH
LHLLL
LHLLH
LHLHL
LHLHH
LHHLL
LHHLH
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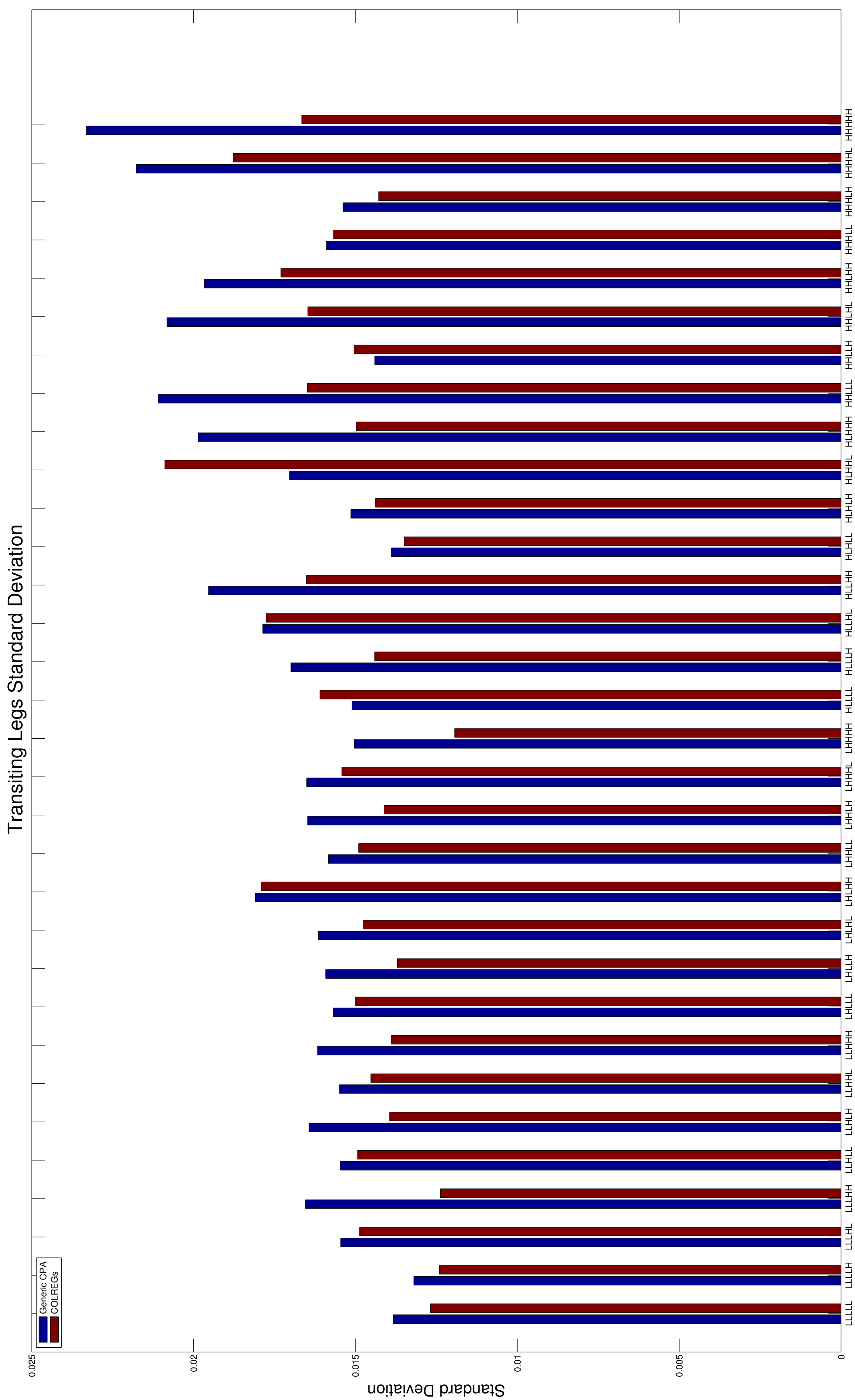
LHHHH
HLLLL
HLLLH
HLLHL
HLLHH
HLHLL
HLHLH
HLHHL
HLHHH
HHLLL
HHLLH
HHLHL
HHLHH
HHHLL
HHHLH
HHHHL
HHHHH


Transiting Legs Standard Deviation
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Generic CPA
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